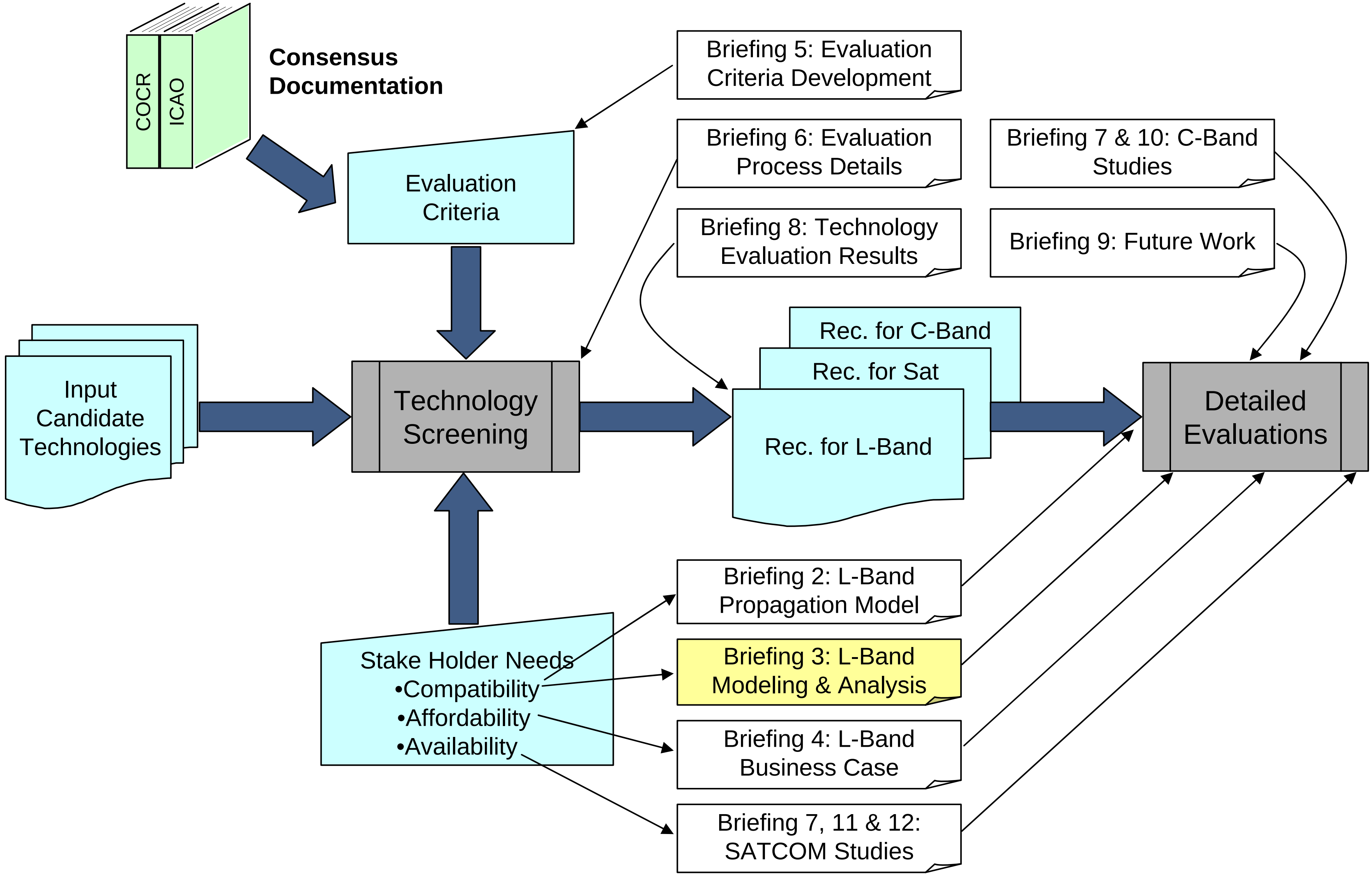
Briefing #3 - L-Band Modeling & Analysis

Future Communications Study

Phase II End of Task Briefing

June 21, 2006

Structure and Content of Today's Presentations



Briefing Outline

- Overview of L-Band Modeling
- Modeling Performed to Characterize P34
  - OPNET Modeling
  - Physical Layer Simulation
- Modeling Performed to Characterize LDL
- Interference Analysis Work
  - DME Modeling
  - Mode-S Modeling
  - UAT Modeling

Overview of L-Band Modeling

- Initial technology pre-screening recommended satellite and terrestrial technologies in several different aeronautical bands
  - Several recommendations were made for using L-Band spectrum
- L-Band recommendations included B-VHF, P34, WCDMA and LDL (VDL3 with a redesigned physical layer)
- Detailed modeling and analysis was undertaken in this phase for a subset of the recommended technologies
  - P34 and LDL were selected for analysis
    - They scored well in initial pre-screening
    - The physical layers of the two technologies are very different
      - Thought to bracket the types of modulation solutions that might be applied
        - » LDL is a single-carrier, simply modulated signal and P34 is an adaptively modulated OFDM waveform

Overview of L-Band Modeling

- P34 Analysis conducted
  - OPNET Modeling – the P34 protocol stack was modeled using OPNET Modeler
    - High fidelity simulation of protocol stack provided insight into technology performance
    - Offered load and scenario as specified in COCR for NAS “Super Sector”
  - Physical Layer Modeling – P34 physical layer was modeled with high fidelity by developing a custom C code application
    - Provided insight into technology performance in aviation environment
    - For performance assessment, C was chosen over SPW and MATLAB Simulink® due to complexity of P34 pilot structure
  - Interference Modeling – a model of the P34 transmitter was developed using SPW to assess P34 interference to UAT and Mode-S Receivers
    - DME receiver modeling was undertaken, but was eventually terminated due to lack of “as built” algorithm information and insufficient fidelity with predictions to known results

Overview of L-Band Modeling

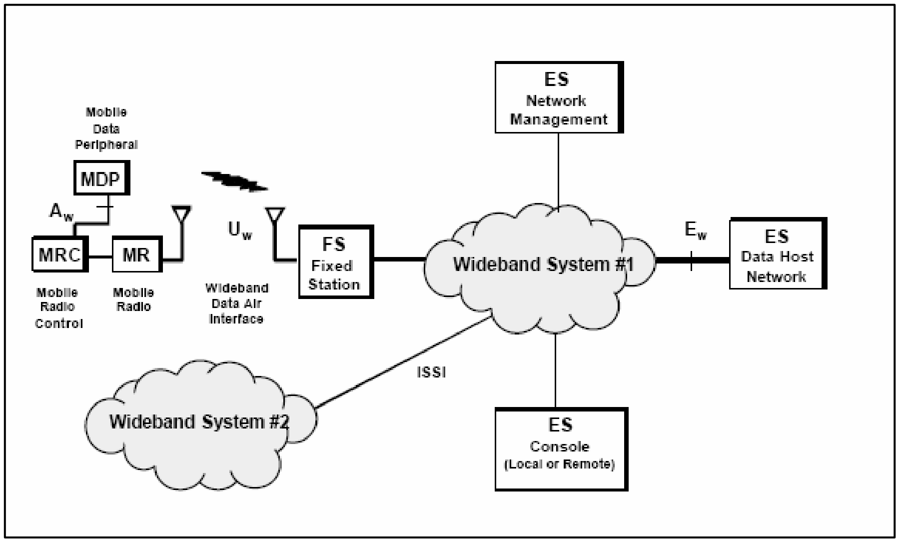
- LDL Analysis Conducted
  - Physical Layer Modeling – LDL physical layer was modeled by developing a simulation of the LDL transmitter and receiver with MATLAB Simulink®
    - Performance of the LDL receiver was predicted for both Gaussian Noise and the dispersive fading A/G channel model developed for the purpose (and described in Briefing #2)
  - Interference Modeling – a model of the LDL transmitter was created using SPW. This model was used to assess the impact of co-channel emissions from an LDL transmitter on
    - UAT Receiver – modeled basic (short) ADS-B messages. Longer messages will have better performance. Selected interference mechanism was BER
    - Mode-S Receiver – selected interference mechanism was probability of correct and false preamble detection
    - As noted, DME Receiver modeling was halted. It is recommended that DME measurements be made against candidate waveform types in Phase III of this study

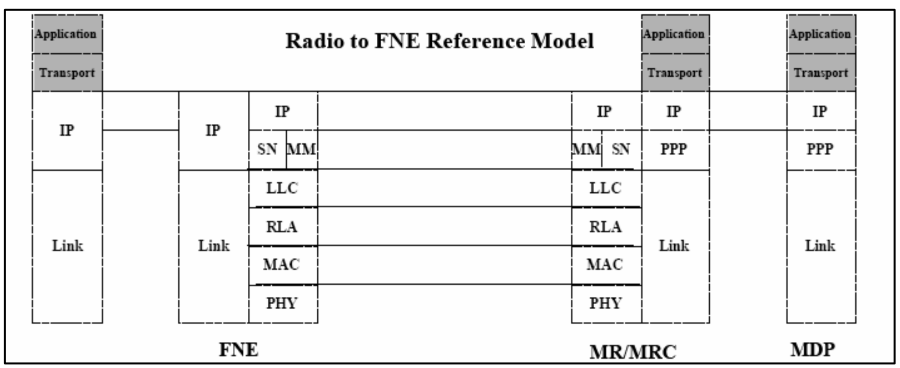
P34 Modeling

P34 Overview

- APCO Project 34 is a EIA/TIA standardized system for provision of packet data services in an interoperable dispatch oriented topology for public safety service providers
- Project 34 concept is a government/commercial partnership
  - Provides universal access to all subscribers
  - Carefully controlled and managed network
- Was developed to address “issues that restrict the use of commercial services for mission critical public safety wireless applications”
  - Priority access and system restoration
  - Reliability
  - Ubiquitous coverage
  - Security

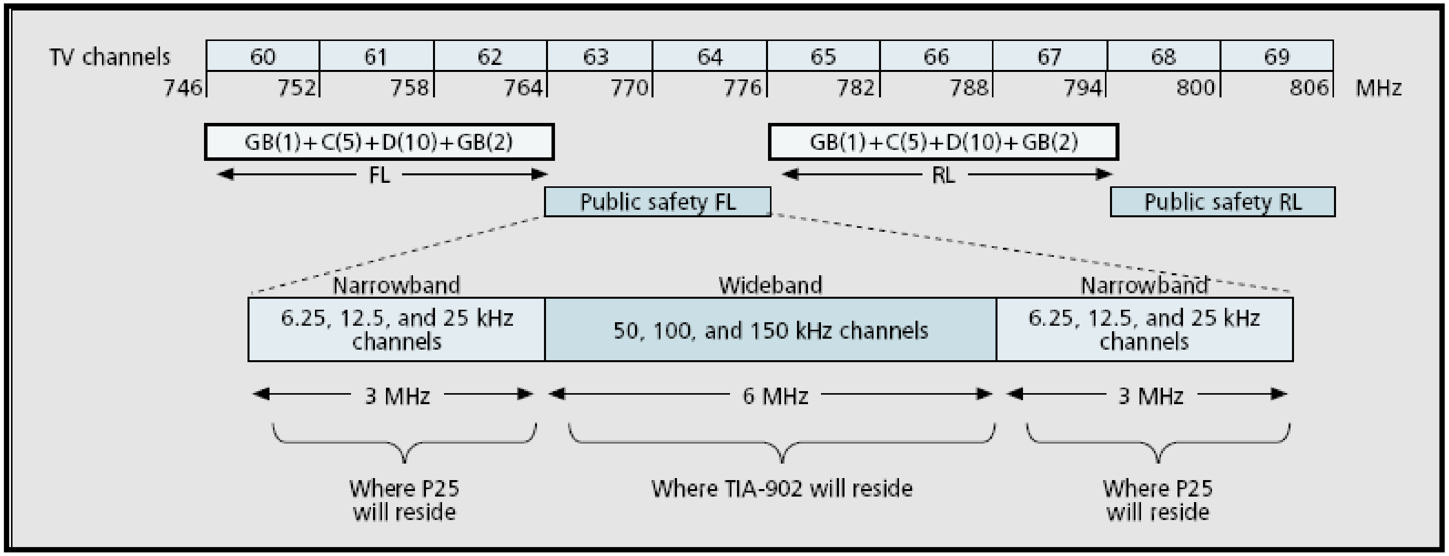
P34 Overview (2)





- A P34 network (called a "Wideband System") can interoperate with other P34 networks (the ISSI standardized interface) with end-systems (Ew interface) and with mobile users over the air interface (Uw)
- The air interface has defined modes between mobiles (MR to MR); between mobiles and fixed infrastructure (MR to FNE) and repeated modes for extending range to distant stations
  - Mobile Radios can serve as repeaters to extend range from FNE to distant Mobile Radios
- The protocol stack is layered, and assumes a point of attachment to an IP network

P34 Overview (3)



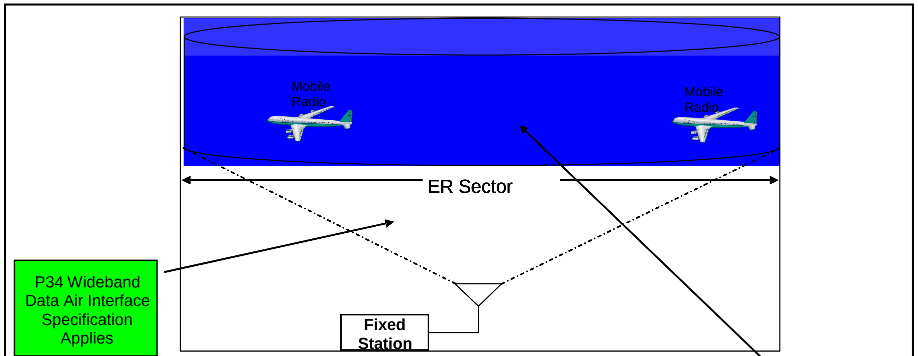
Source: "Spectrum Considerations for Public Safety in the United States", Tewfik L. Doumi, IEEE Communications Magazine, January 2006

- P34 systems (shown as TIA-902 in the figure) are slated to be deployed using Frequency Division Duplexing with
  - Forward Link (Fixed Network Equipment, FNE, to Mobile Radios, MRC) between 767 and 773 MHz as shown in the figure
  - Reverse Link (MRC to FNE) between 797 and 803 MHz
- The band could be cleared in some areas by December 31, 2006
  - Provided at least 85% of households have digital capable TV sets
- Most likely date is (hard requirement) January 2009

P34 OPNET Modeling

Context of Simulation

- Operational Scenario
  - Modeled region corresponds to the COCR defined “NAS Super Sector”
- Communication Nodes
  - One fixed station node as ground station
  - 95 mobile nodes as the airplanes
- Communication Links
  - P34 SAM Air Interface
    - 50 kHz channels and QPSK modulation – provides 76.8 kbps
    - Lowest defined P34 data rate - should be able to close the link for sector size shown in COCR
- Simulation Goal: Establish whether P34 meets COCR performance requirements



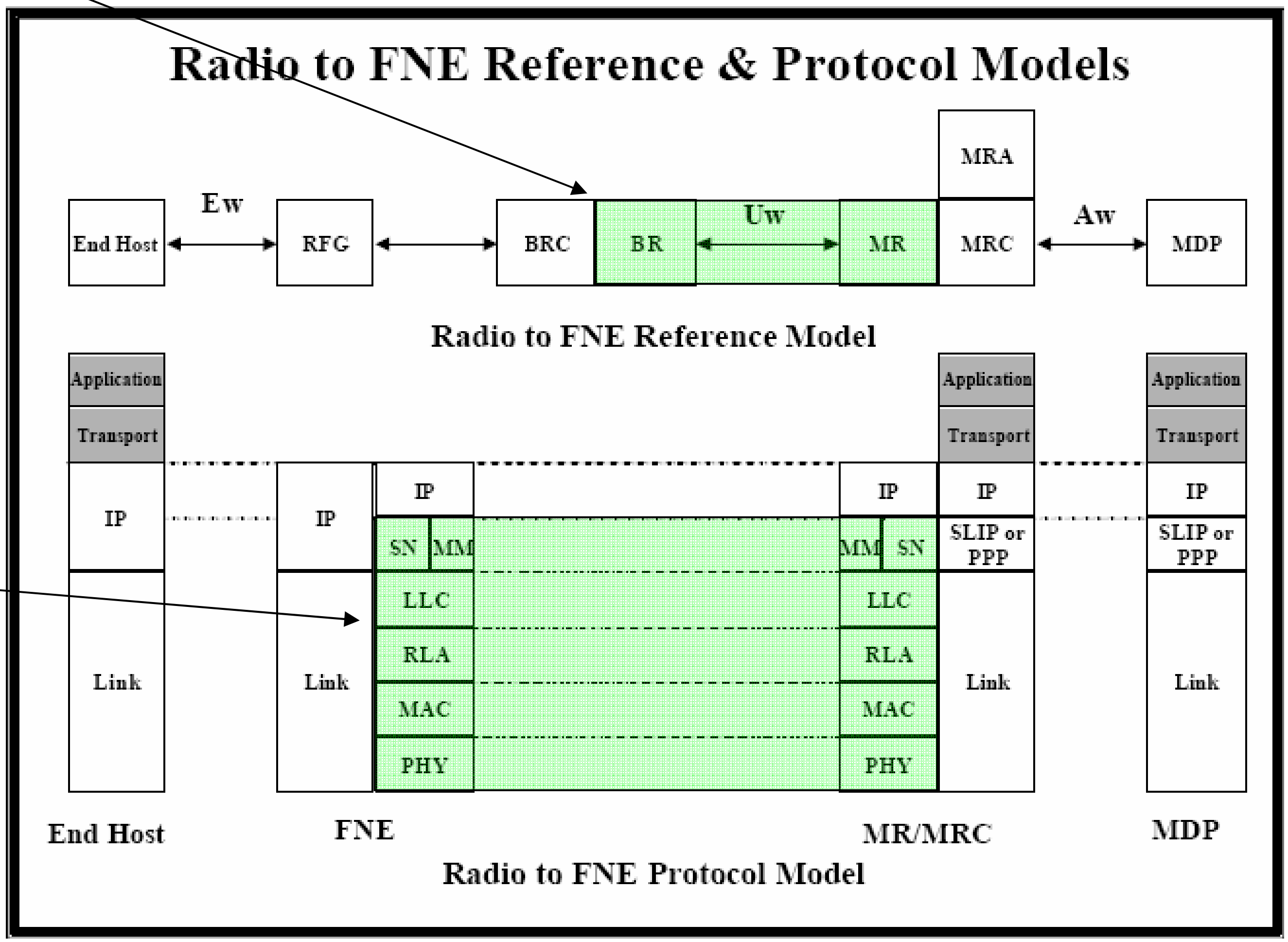
Sector Name	PIAC	Volume (nm^3)	Aircraft per nm^3
En route (ZTL 16)	22	9816	0.0022
En route HD (ZTL 19)	52	7300	0.0071
En route (ZTL 20)	21	14880	0.0014
Super Sector	95	31996	0.0029

Table 7-6 Phase 2 NAS En Route Super Sector Density Calculation

P34 Elements That Were Simulated

Configuration that was simulated was the fixed-network equipment (FNE) to mobile radio (MR). The MR to MR and repeater modes were not simulated. The modeled configuration aligns with the P34 "concept of use".

The custom OPNET development included modeling of the P34 PHY, MAC, LLC and SN Layers.



P34 Elements That Were Simulated (2)

- PDS/SNDCP Functions Modeled
  - PDP Context Maintenance
    - IP Addressing
    - PDP Context activation
    - PDP Context deactivation
  - Management of Data Transfers
    - LLC UP Link maintenance
    - Unicast IP datagrams
    - MRC to FNE SNDCP data transfer
    - FNE to MRC SNDCP data transfer
- LLC Functions Modeled
  - Acknowledged Signaling
  - Acknowledged Data Transfer
  - Flow Control

P34 Elements That Were Simulated (3)

- MAC functions modeled
  - Logical channel management and synchronization
    - Random Access Channel
    - Slot Signaling Channel
    - Packet Data Channel
  - Channel access, allocation of bandwidth, and contention resolution
    - Priority queuing
    - Slotted-aloha reservation requests
- PHY Layer modeled
  - Modeled the SAM interface with the following parameters
    - 50 kHz channel configuration (8 RF Subchannels, 5.4 kHz spacing)
    - QPSK Modulation with Root Raised Cosine filtering (α = 0.2)
    - 76.8 kbps data rate
    - Coherent demodulation using pilot symbols

Simulation Offered Load

- To create the simulation data load, COCR data have been characterized in OPNET tasks, applications and profile management
- COCR data utilized includes
  - message sizes
  - suggested classes of service
  - required latencies
  - aircraft count per domain
  - times in service volumes
  - message repetition frequencies

Services	Uplink	Downlink
ACL	4 x 91	4 x 91
ACM	2 x 107	2 x 88
ADS-B	1 x 34	
A-EXEC	1 x 600	1 x 100
AIRSEP	6 x 497	
AMC	1 x 89	0 x 0
ARMAND	1 x 260	1 x 88
C & P	4 x 91	4 x 91
COTRAC (Interactive)	3 x 1969	4 x 1380
COTRAC (Wilco)	2 x 1613	2 x 1380
D-ALERT	1 x 88	1 x 1000
D-ATIS (Arrival)	5 x 100	3 x 93

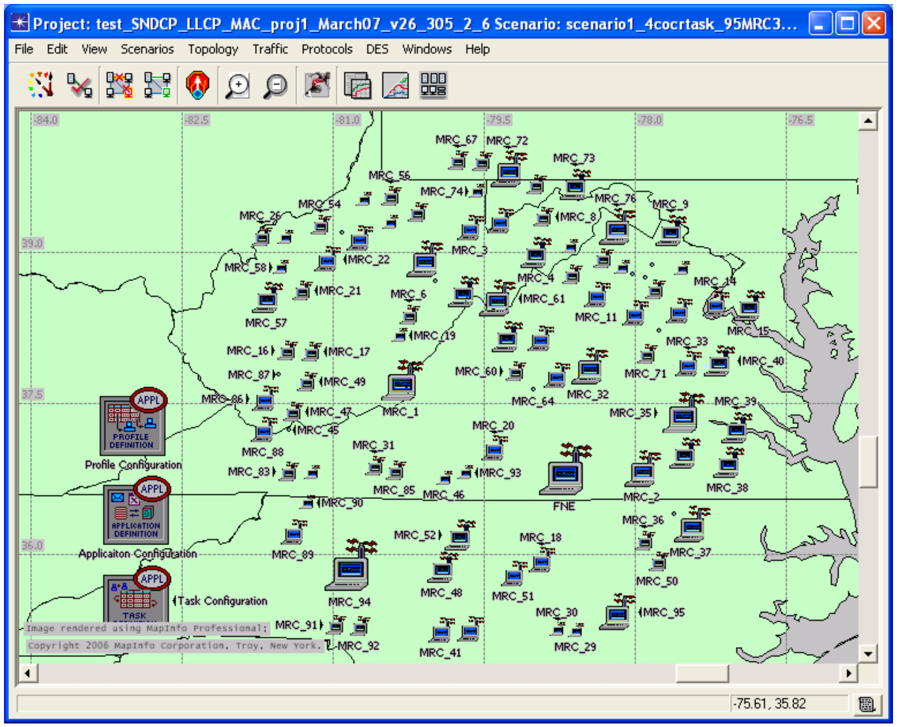
COCR Table 6-12: Message Quantities and Sizes (Excerpt)

Service	Type[7]		APT	TMA	ENR
	I	II			
ACL	X	X	Type I&II: 1 (in ground position), both departure and arrival	Type I&II: 2 per sector, both departure and arrival	Type I: 5 per domain Type II: 1 per domain
ACM	X	X	3 per domain (1 in each position), both departure and arrival	1 per sector, both departure and arrival	1 per sector
ADS-B	X	X	Once every 1 s	Once every 3 s	Once every 3 s
A-EXEC** (per service volume)	-	X	0	1 per year per domain	1 per year per domain

COCR Table 6-9: Service Instances (ATS) – Phase 2 (Excerpt)

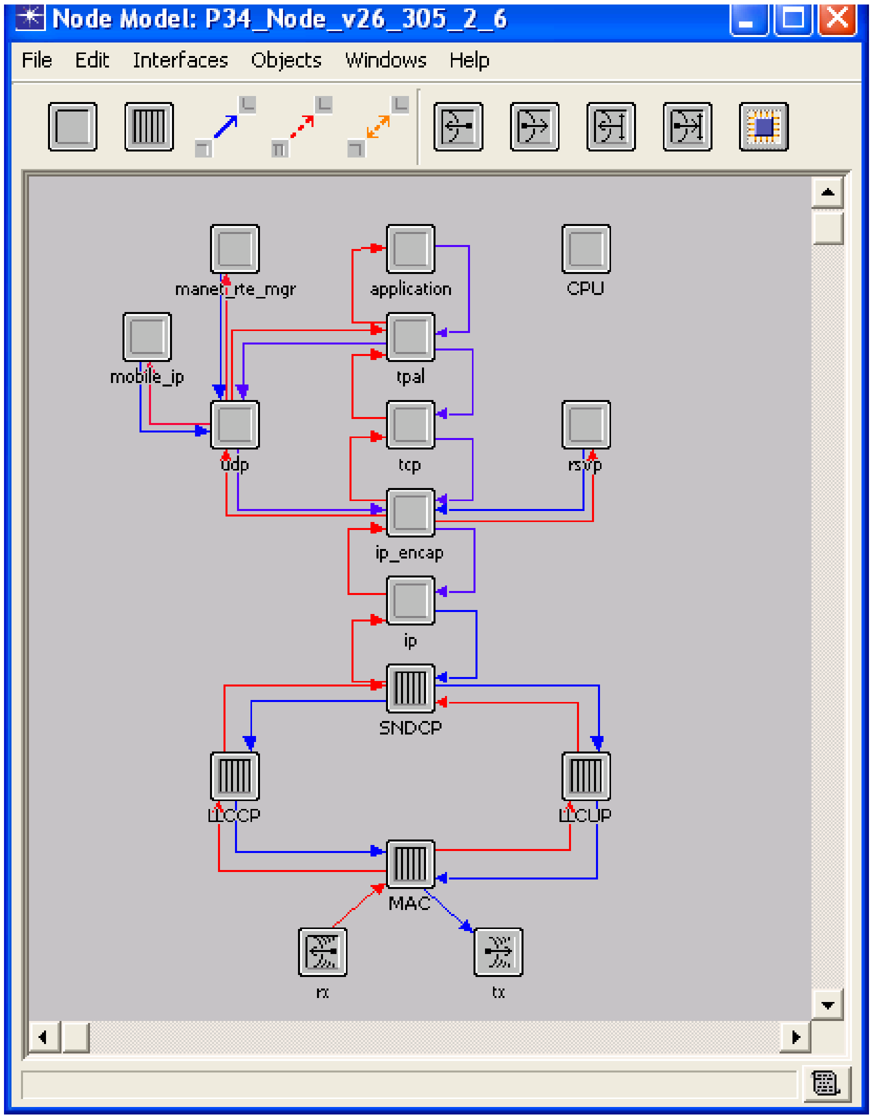
P34 OPNET Models

Network Model



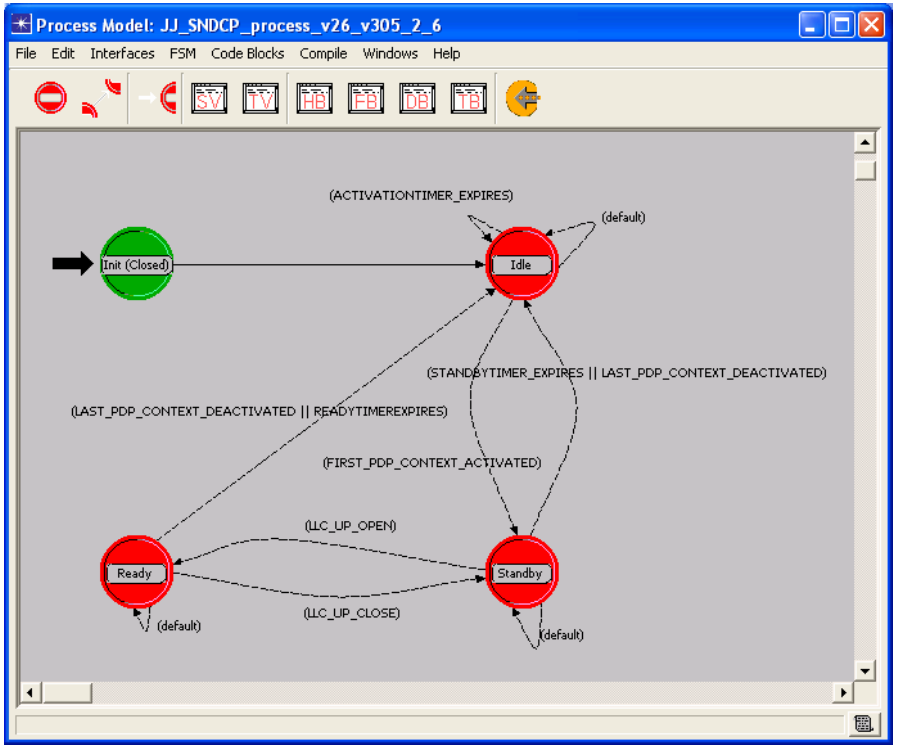
- The Network Model is the highest order in the OPNET Modeler Hierarchy
- The modeled configuration was the NAS ‘super sector’ as described in the COCR
- The ‘super sector’ includes one ground station (FNE) and 95 aircraft (MRC)
- The COCR described messages, rates and size distributions are modeled using the task, application and profile configuration blocks

P34 Node Model



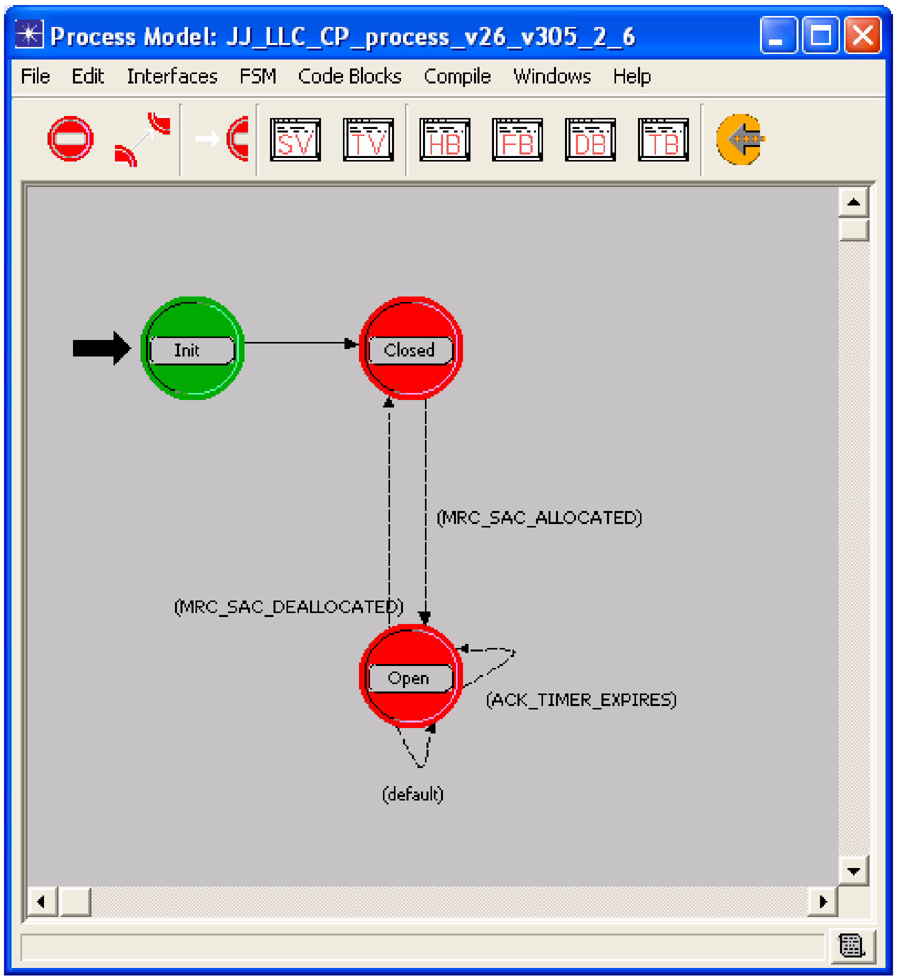
- The Node Model is the second layer in the OPNET Hierarchy
- This is the node model for both MRC and FNE
- Based on OPNET wireless LAN server node model
- Customized SNDCP, LLC CP, LLC UP, and MAC processes
- Transmitters and Receivers are configured to the P34 physical layer

SNDCP Process Model



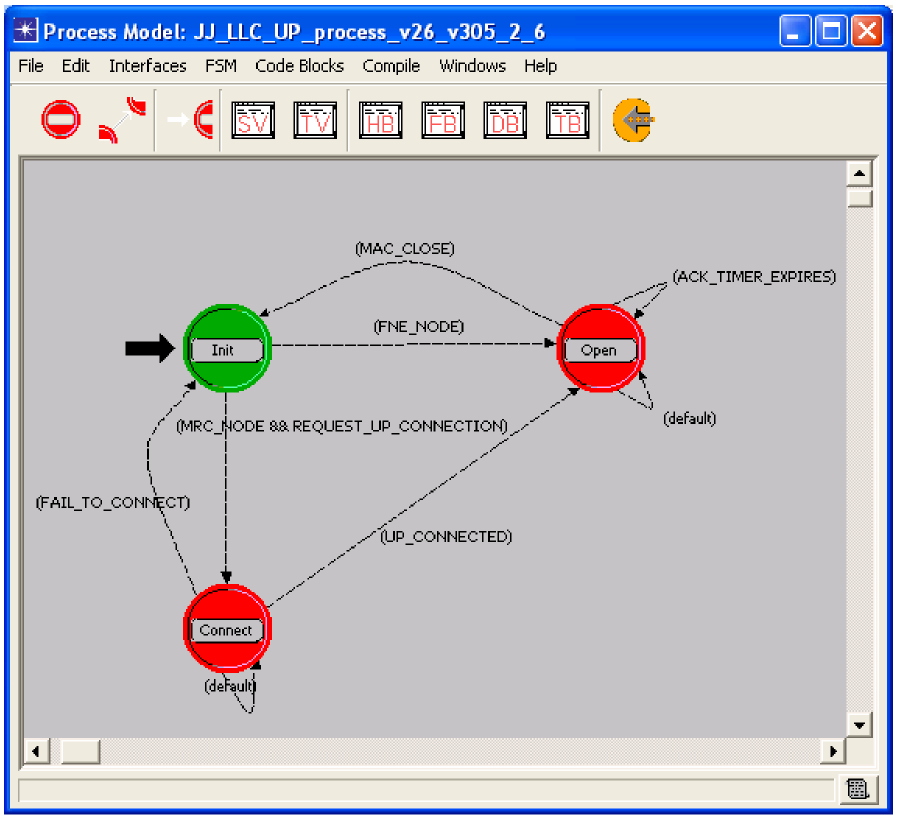
- The custom process models are the lowest level of the OPNET hierarchy
- The SNDCP process model is shown here. It is coded as a set of states and transition rules. Defined states:
  - **Init state –** Initializes setup and variables of the program
  - **Idle state –** No context is activated
  - **Standby State –** At least one context is activated, but no UP connection yet
  - **Ready State –** Exchange data

LLC CP Process Model



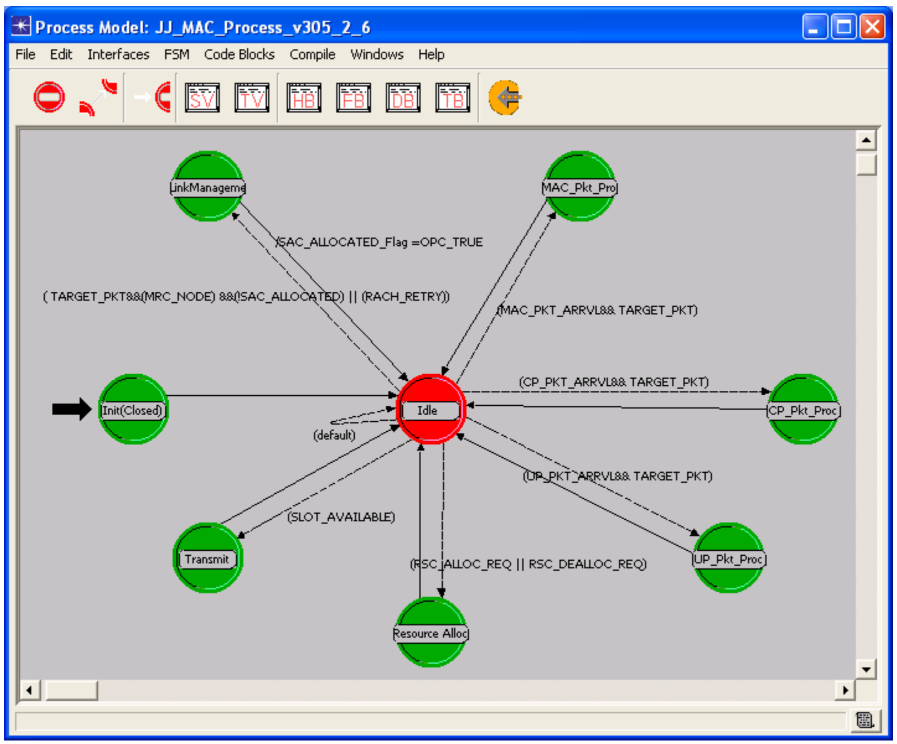
- **Figure shows the custom Link Layer Control Plane (LLC CP) State Transition Diagram**
  - Programmed in C code and OPNET Kernel Procedures (KPs)
- **Has the following defined states:**
  - **Init state –** Initializes setup and variables of the program
  - **Closed State –** Successful FNE configuration and WAI address (SAC) is allocated
  - **Open State –** LLC accepts service requests

LLC UP Process Model



- **Figure shows the custom Link Layer User Plane (LLC UP) State Transition Diagram**
  - Programmed in C code and OPNET KPs
- **Has the following defined states:**
  - **Init state –** Initializes setup and variables of the program
  - **Connect State –** Request to set up UP connection
  - **Open State –** Accepts user data transmission service requests

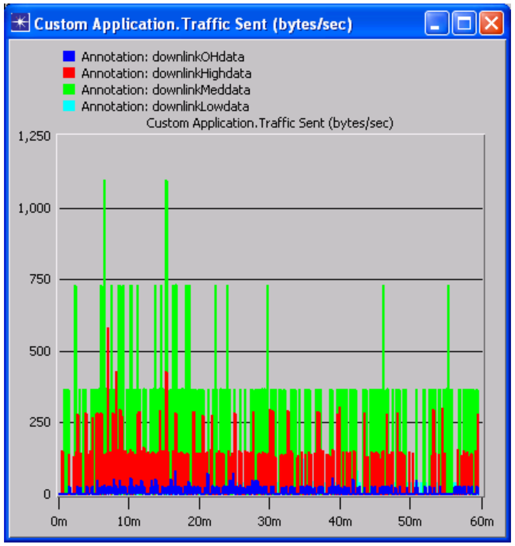
MAC Process Model

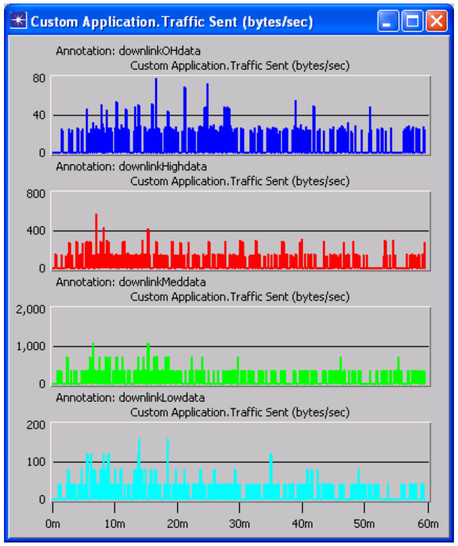


- **Custom MAC has the following defined states:**
  - **Init state –** Initializes setup and variables of the program
  - **Idle State –** Accept service requests and decides next processing state
  - **Link Management State –** MRC uses RACH to request a SAC
  - **MAC_Packet_Process State –** Process incoming MAC packets
  - **CP_Packet_Process State –** Process incoming CP packets
  - **UP_Packet_Process State –** Process incoming UP packets
  - **Resource Allocation State –** Allocate time slots
  - **Transmit State –** Transmit packet when time slot is available

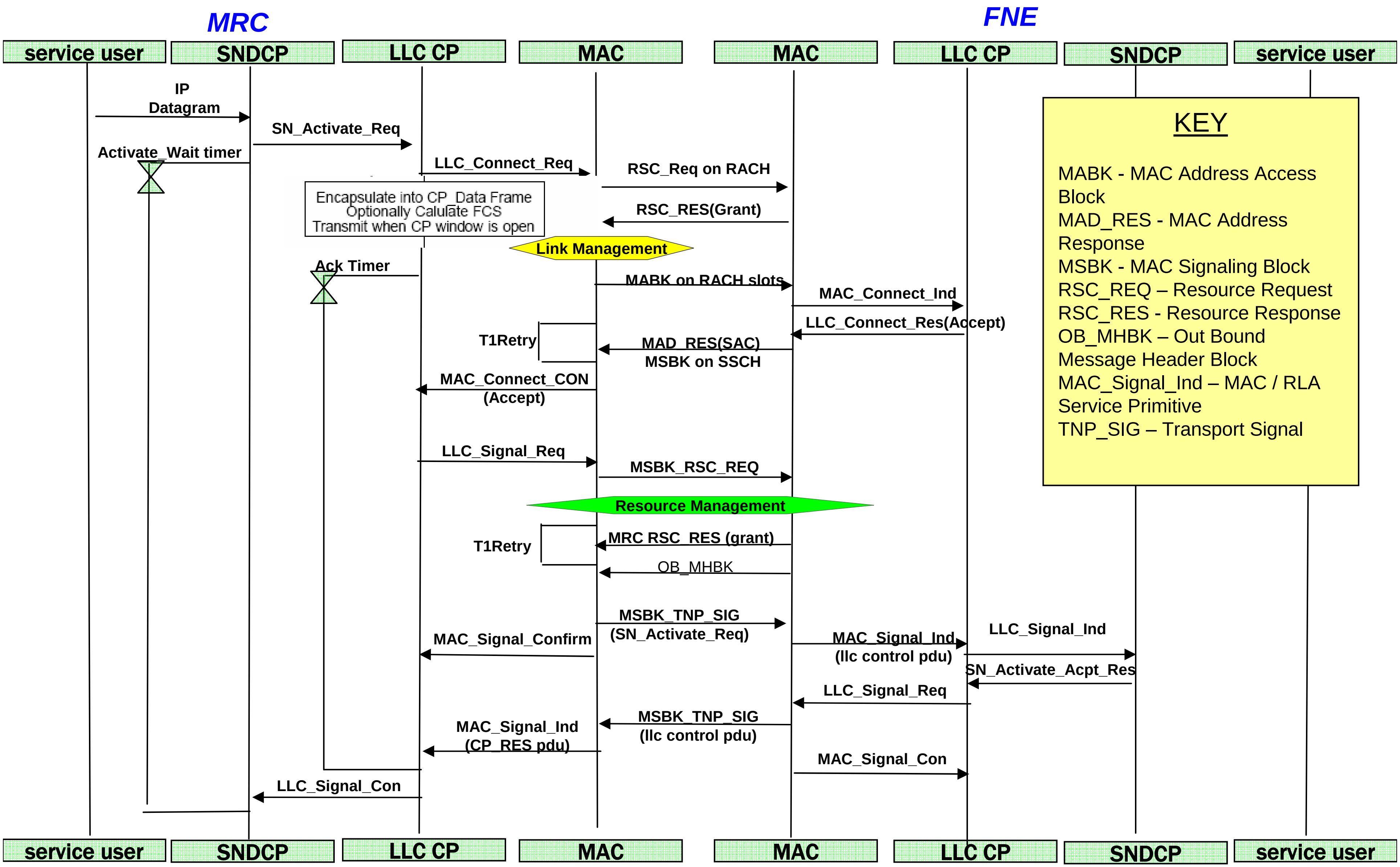
Traffic Sent (Bytes/Second)
95 MRCs

- **The figures show the OPNET simulation offered load**
  - 95 Airplanes (MRCs)
  - Simulation duration is on the ordinate – simulation duration was one hour
  - Abscissa is the peak load by traffic class in bytes per second
- Simulation uses same QoS classifications as are suggested in the COCR
  - Load is not staggered – all 95 aircraft are assumed in the airspace at the start of the simulation
  - There is some start up loading as all of the mobiles attempt context activation

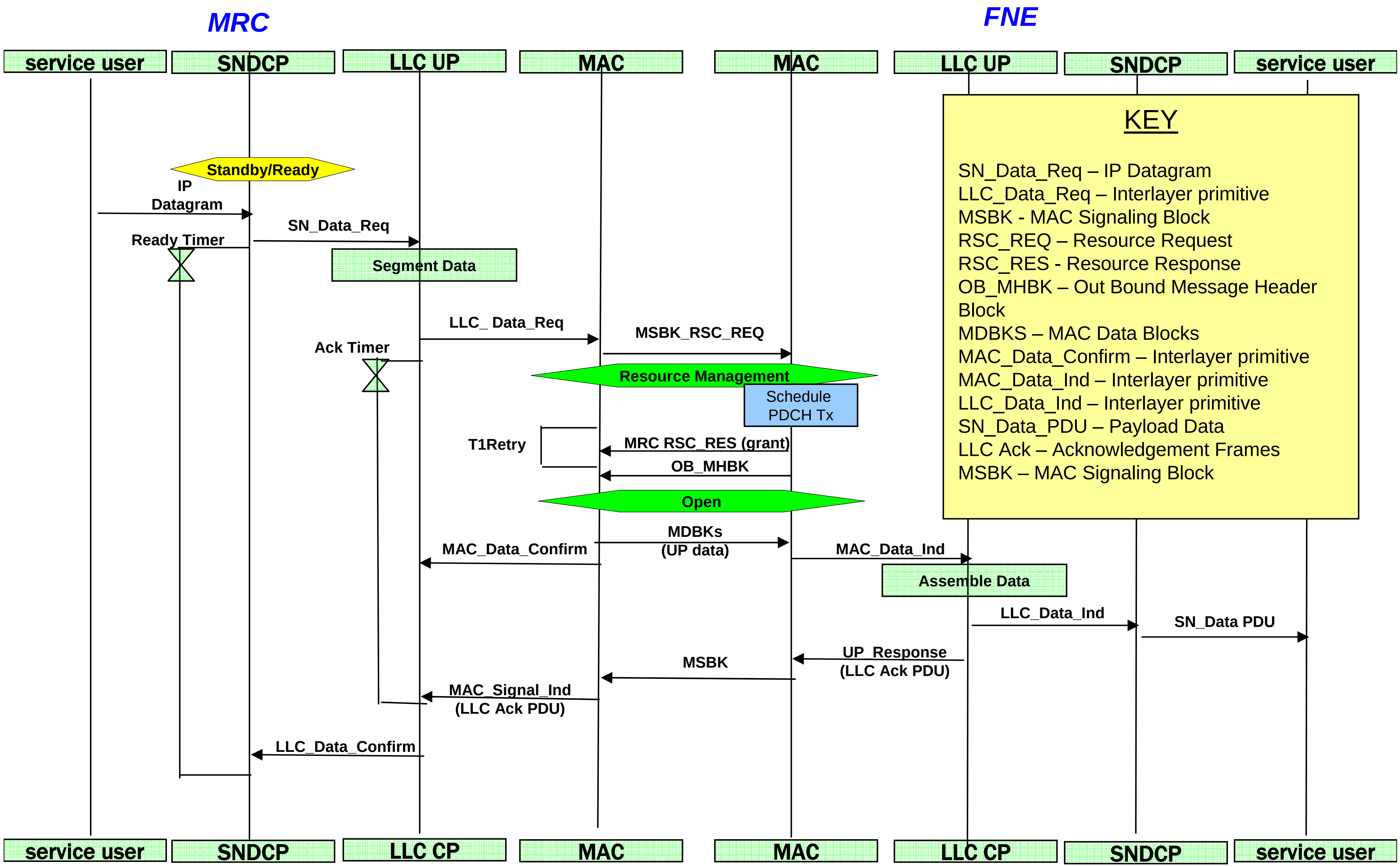




SNDCP Context Activation Sequence Diagram

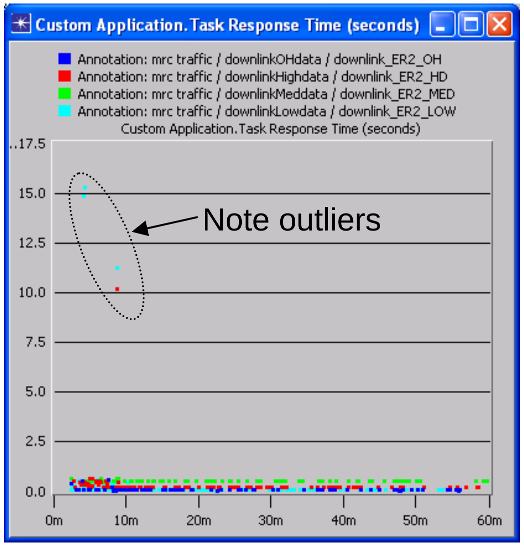


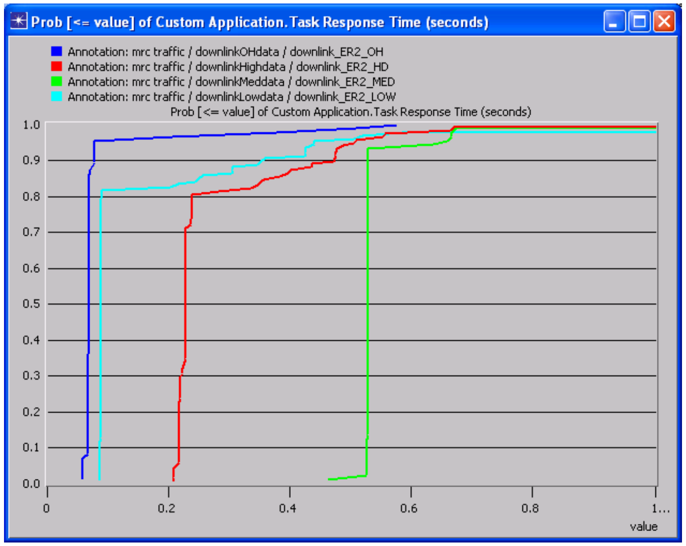
UP Acknowledged Data Transmission Sequence Diagram

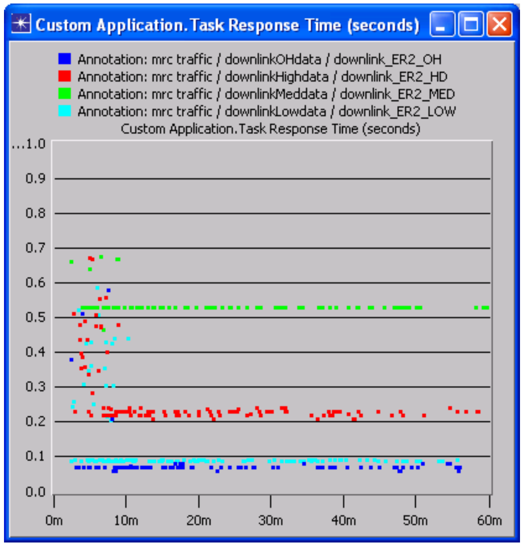


Simulation Outputs (Results)

- The figures show the response time of the P34 simulation to the offered load for each of the transmitted messages
- It seems that sub-network latencies over P34 protocols (SNDCP, LLC CP, LLC UP, MAC) meet COCR latency requirements
  - Some startup outliers, but 95% is under 0.7 seconds





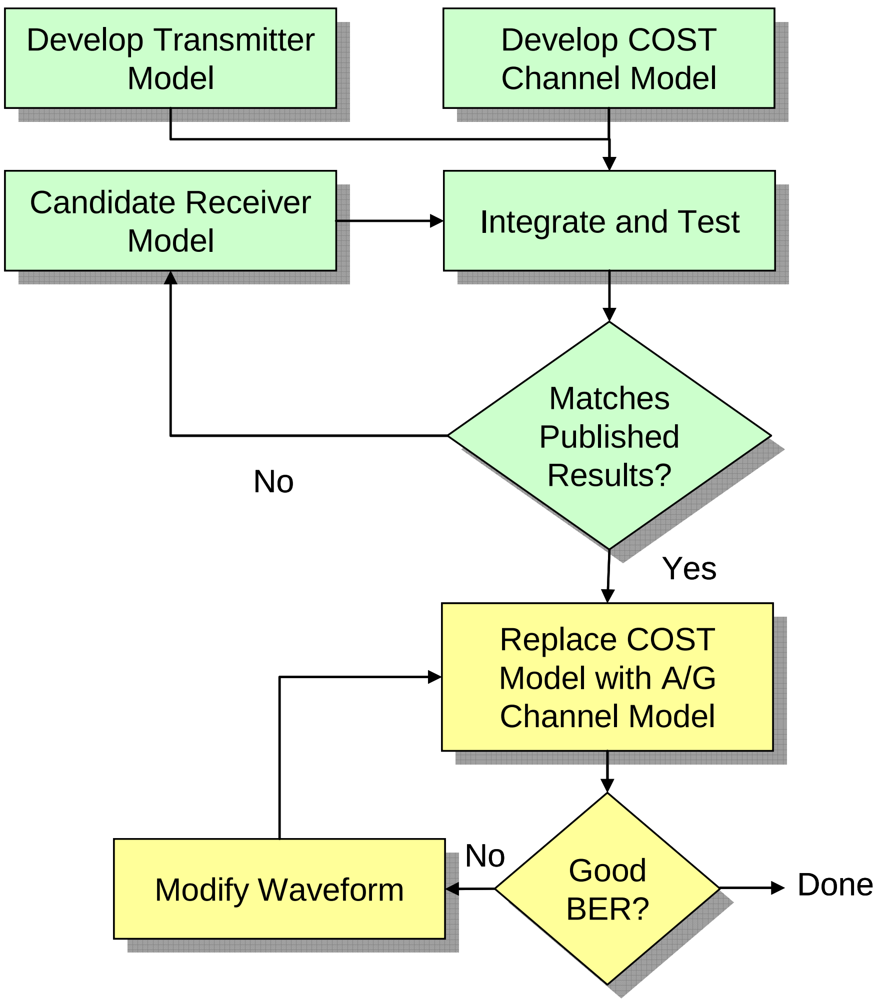


P-34 Physical Layer Modeling

Task Objective and Methodology

- The objective of this task was to develop a physical layer simulation of P34 and to estimate the performance in the expected propagation environment
- Methodology
  - Develop physical layer model of technology
  - Validate and iterate as required with known results
    - Most standards define the transmitter implementation, but only provide required receiver performance
    - Some iteration of receiver implementations (various algorithms for pilot estimation and the like) are required to achieve required performance
    - In the case of P34, the required performance was specified in the context of a particular channel model
      - This model, a COST207 model, HT200 and TU 50, is not applicable to the projected use of the technology, but had to be simulated to verify receiver implementation
  - Introduce L-Band channel model and assess performance
    - Make modifications to standardized waveform as required to optimize performance

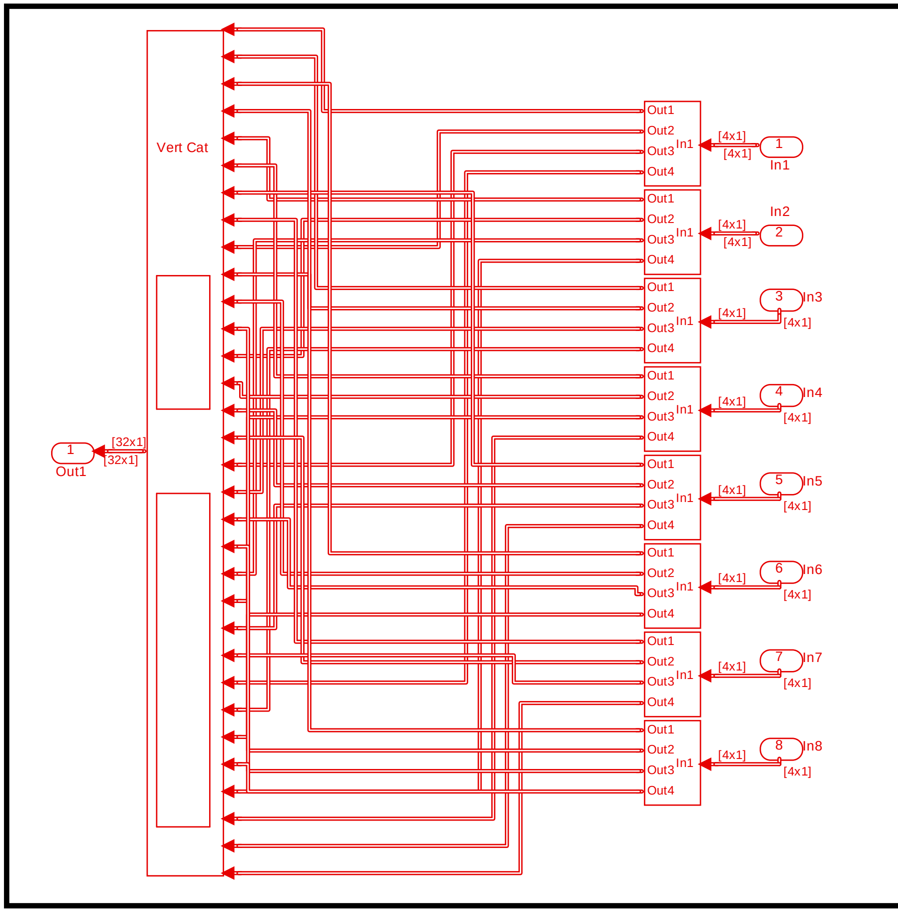
Overview of Approach

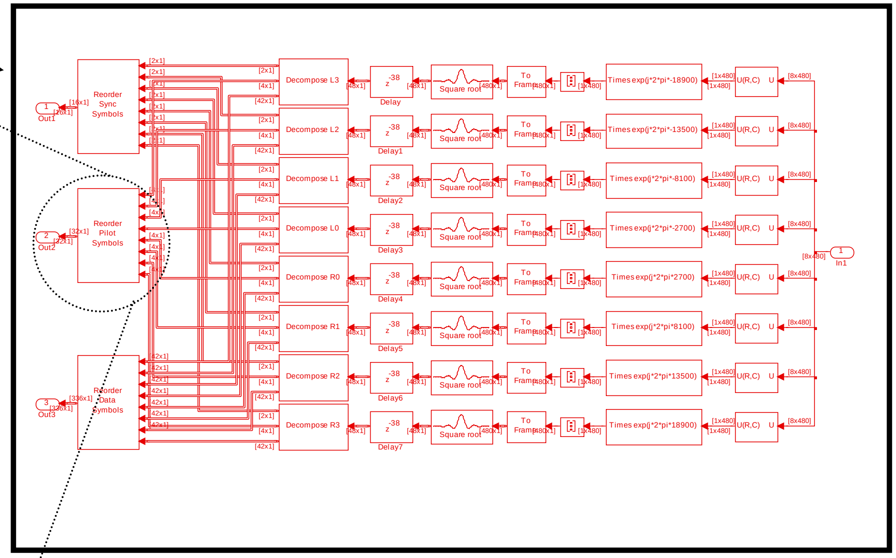


- The green colored processes are Phase II activities (current work phase) that were completed and described in the November status briefing.
  - P34 transmitter and receiver models developed using C code
  - COST model implemented, and published results replicated
- This briefing provides
  - Brief overview of the Phase II work as reported in November
  - Detail on further Phase II work completed since November
    - Expected coding gains
    - Required model changes
    - Expected P34 performance in A/G channel

Selecting the Right Tool*

MATLAB Simulink Model of
P34 Rx (partial)



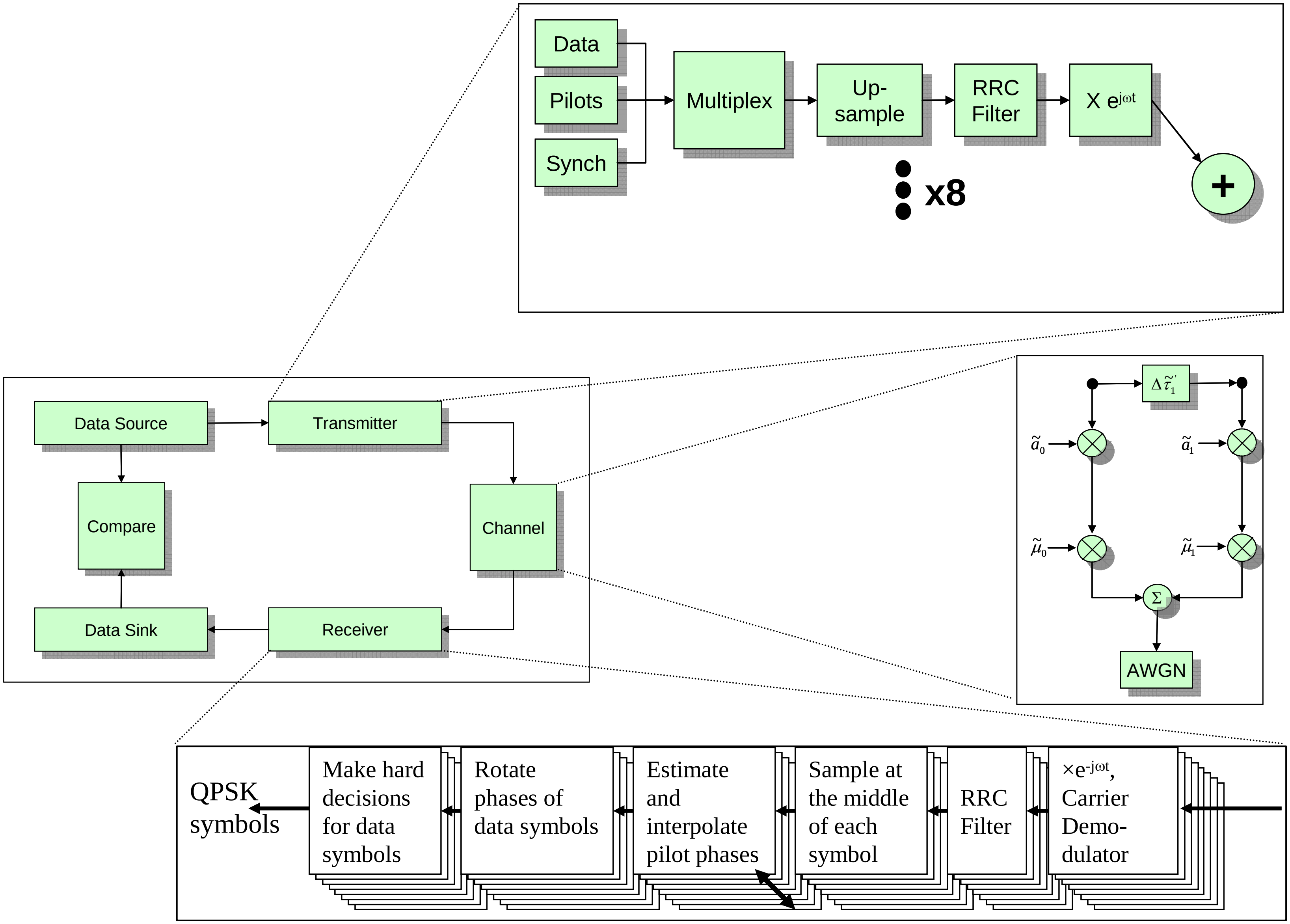


*There are at least 10 different kinds of hammers. Not all should be used for finish carpentry.

- The P34 pilot locations (interspersed throughout the data) make Simulink a poor choice as a modeling environment
- A custom C code simulation was developed that replaces all of the Simulink complexity shown here with a few lines of code

```
for (nb = 4; nb < 48; nb+=12)
{baud[nb].symbol[0] = pilotValue;
baud[nb].symbol[2] = pilotValue;
baud[nb].symbol[5] = pilotValue;
baud[nb].symbol[7] = pilotValue;}
```

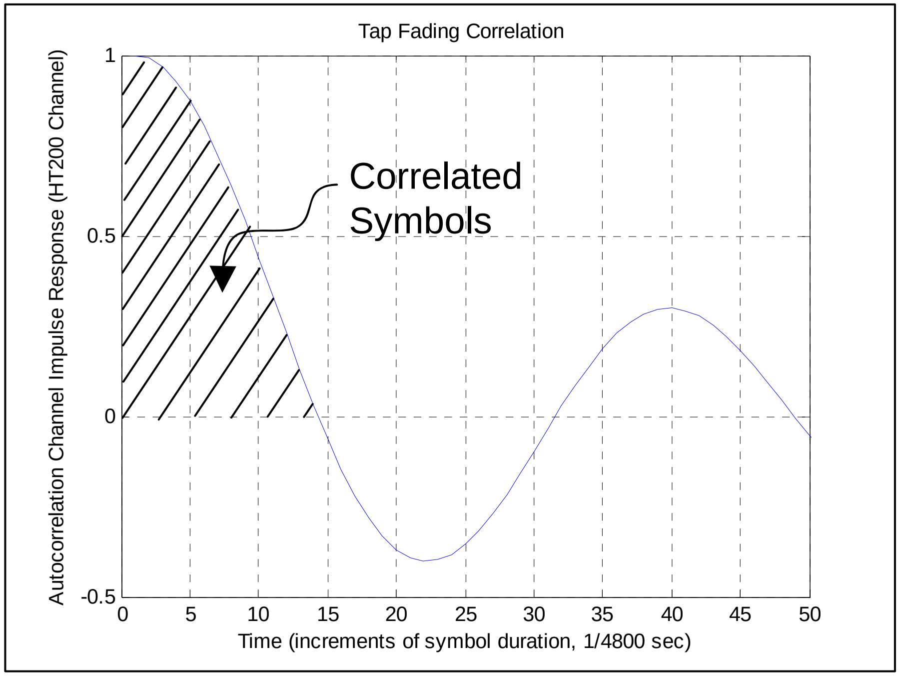
Physical Layer Simulation Block Diagram



P34 Modeling – Time Correlations of Fading Process

- Each tap in the Rayleigh model is time-correlated
  - The scale of time correlation is a function of the maximum Doppler speed
  - If tap fading process is modeled using the Jakes Doppler spectrum, the autocorrelation function for the impulse response of the channel is a 0^{th}-order Bessel function of the first kind with an argument that is $2\pi f_{max}\tau$
- For HT200 model (200 km/h max Doppler speed) and f=750 MHz, correlation decays over ~14 bauds
  - Time separation between pilot symbols in the same subchannel is 12 bauds

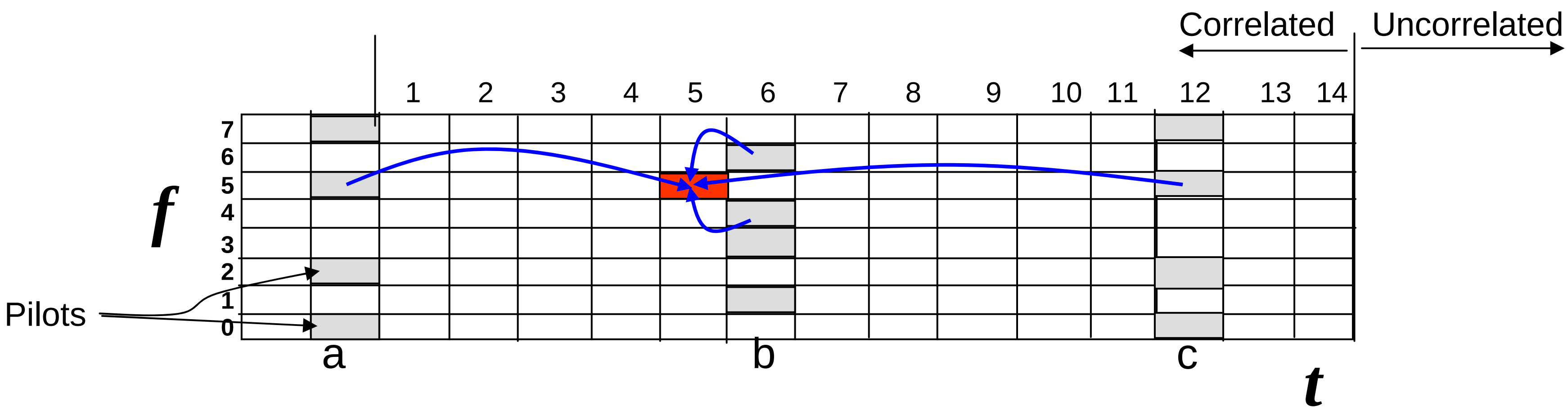
HT200 Channel Impulse Response
V = 200 km/Hr, f = 750 MHz



Graphic from MATLAB. Details of theory can be found in “Mobile Fading Channels”, Matthias Pätzold, p 46

P34 Modeling – Channel Est. Interpolation Weighting

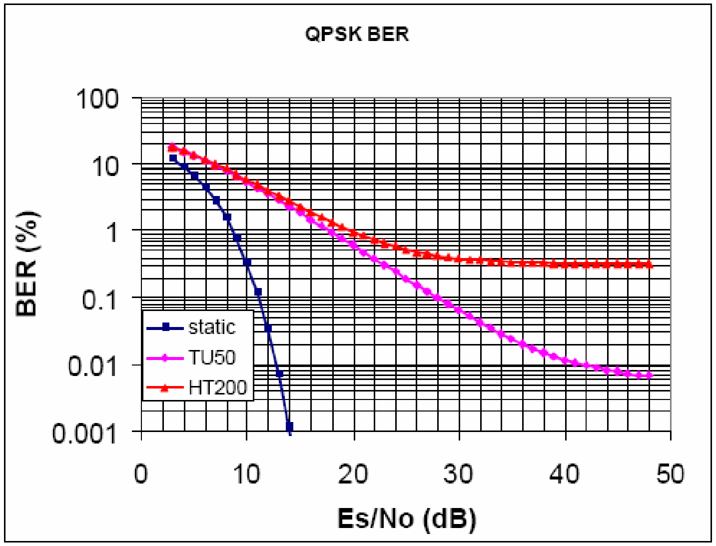
- Phase rotation for a data symbol is computed as a weighted sum of phase rotations for contributing pilot symbols
- Contributing pilot symbols are limited to those in proximity of the data symbol in time and frequency
  - Only pilot symbols within 9 bauds and within 1 subchannel of the data symbol are used

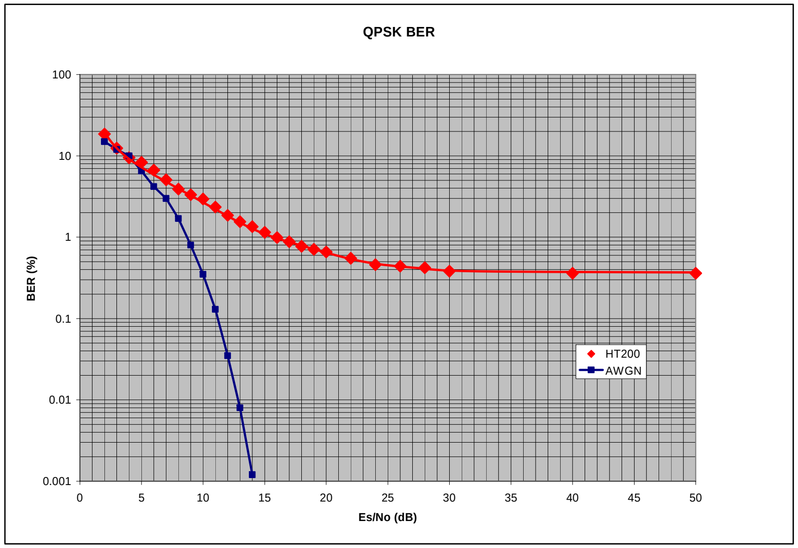


- Weights are smaller if time separation from the pilot is larger
- Weights are smaller if the pilot amplitude is small
  – This weighting algorithm mitigates effects of fades

P34 Modeling – Validation of Receiver Model

- The P34 Scaleable Adaptive Modulation (SAM) physical layer interface was modeled by developing a custom application using C code
- The transmitter was implemented as detailed in the specification for the 50 kHz channel using QPSK modulation
  - Channel coding and interleaving were not modeled
- The receiver implementation was tested against known results
  - Top figure is from Annex A of TIA-902.BAAB-A
  - Bottom figure shows simulation results for AWGN and the HT200 channel model





An Aside about the Channel Model Used for Validation

- Both the TU50 and HT200 models are COST suggested models for terrestrial (mobile) communications
  - TU50 is the COST “Typical Urban” 50 km/h and is implemented as:
    - Two taps, <u>both</u> Rayleigh Faded (no direct path)
    - One tap is delayed and attenuated by 5 μs and -22.3 dB
  - HT200 is the COST “Hilly Terrain” 200 km/h only is implemented as:
    - Two taps, <u>both</u> Rayleigh Faded (no direct path)
    - One tap is delayed and attenuated by 15 μs and -8.6 dB
- The suggested aeronautical channel model <u>might</u> be less severe than the two models shown on the previous slide
  - No resolvable multipath → flat fading
  - Large K-factor → Dominant LOS component
  - However, very high Doppler implies channel coherence time is <u>less</u> than pilot structure of P34 can support

P34 Modeling – Investigation of Coding Gain

- From the previous results, it was unclear if satisfactory performance was being achieved in the mobile fading channel
  - Needed to know what a raw BER of $3*10^{-3}$ translated to after coding
- P34 SAM uses a system of concatenated Hamming codes. The basic scheme is shown in the top figure
  - Simulated the rate ½ coding by concatenating two Hamming coders and a block interleaver
- Coding gain is shown in bottom figure
  - $3*10^{-3}$ raw BER (we will refer to this as the 'threshold' later) is approximately 10^{-5} coded BER

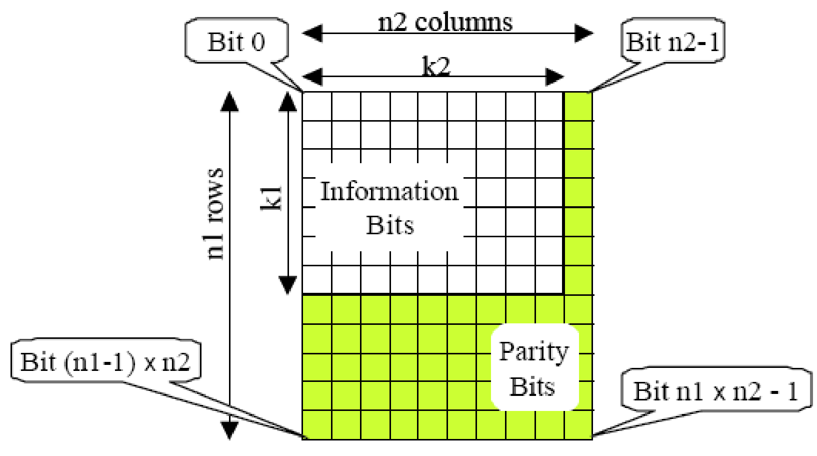
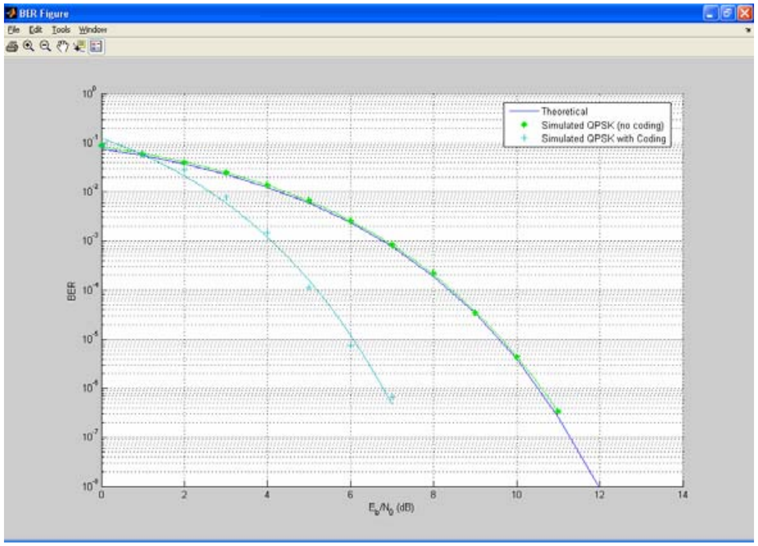


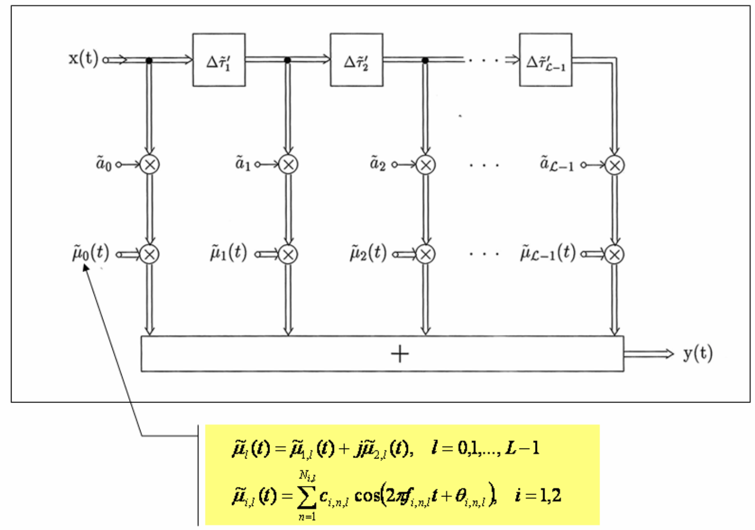
Figure 5. Block Code Construction



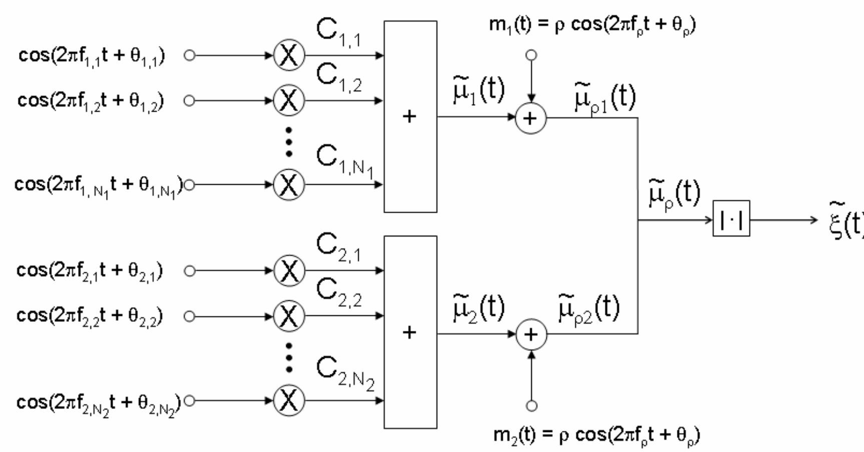
Changes Required to Simulation to Model Rician Channel

- The COST models require a Rayleigh faded channel
  - Implemented using the method of exact Doppler
- Model has to be modified to produce Rician statistics
  - New channel model shown in bottom figure

Overall Channel Model

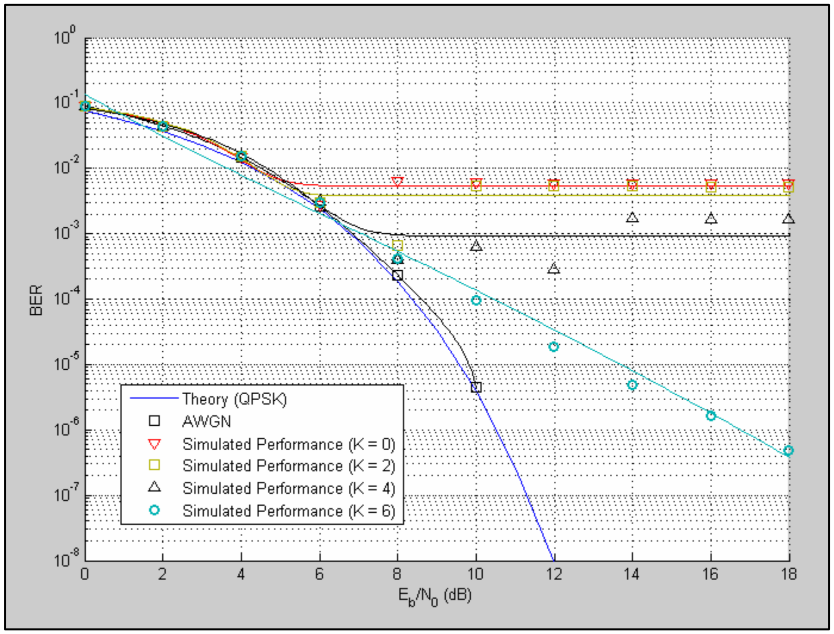


Rician Process from Colored Gaussian Noise



Simulated P34 Performance in the Aeronautical A/G Channel

- The A/G channel was simulated using a two tap model
  - Tap 1 was modeled as Rician, with a K-factor of 18 dB, unity gain, Jakes Doppler Spectrum
  - Tap 2 was modeled as Rayleigh, with a 4.8 μs delay, -18 dB average energy, Jakes Doppler
- The mobile velocity was taken to be 0.88 mach
  - COCR gives this as the maximum domestic airspeed based on Boeing 777 maximum speed of 0.88 mach
- P34 tuned frequency was taken to be 1024 MHz
  - Maximum Doppler shift - 1022 Hz
- P34 performance is expected to be acceptable – work is being validated



Conclusions

- The P34 pilot structure is not robust enough to work n a Rayleigh faded channel at aircraft speeds

- However, initial simulations indicate good performance can be achieved in the aeronautical channel
  - Primarily a consequence of the strong LOS component of the received signal

- These are initial results and are still being validated

LDL Modeling

LDL Overview

- LDL is VDL3 with a redesigned Physical Layer and slight modifications to the Link Layer to facilitate operation in L-Band (960-1024 MHz)
  - LDL uses a modified version of the UAT Physical Layer (lower data rate) and VDL3 for all other layers

- Physical Layer Modifications:

	VDL3	LDL	UAT
Modulation	D8PSK	BFSK	BFSK
Data Rate	31.5 kbps	62.5 kbps	1.041667 Mbps
Synchronization Preamble	16 8-ary symbols	36-bit sequence	36-bit sequence

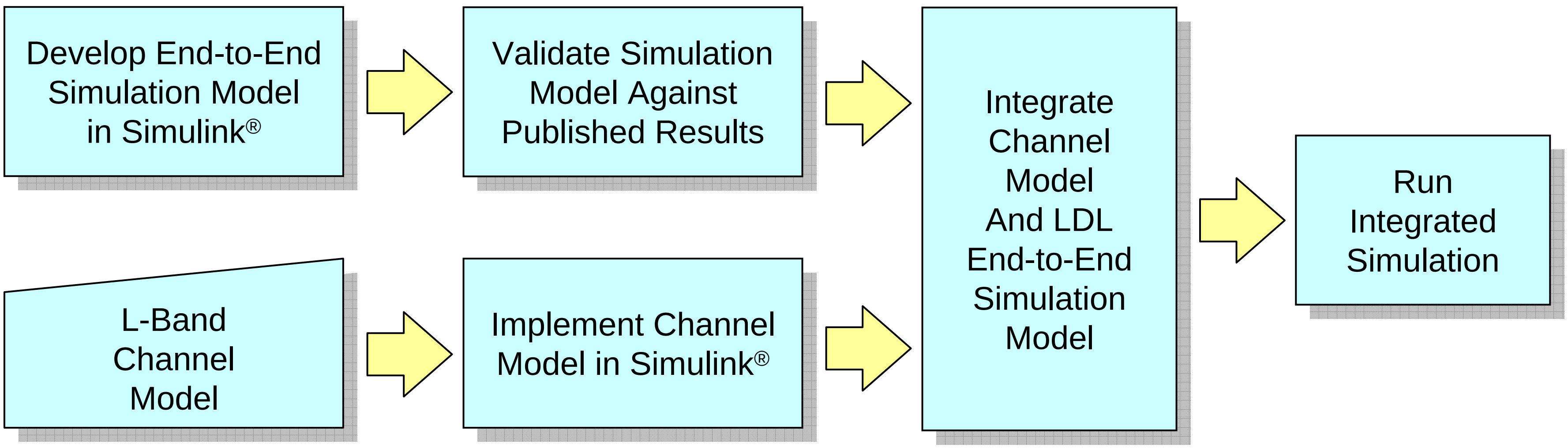
- Link Layer Modifications:
  - Increase guard time
  - Increase # of time slots
  - Increase lengths of various message types

LDL Overview (2)

- The objective of this task was to develop a physical layer simulation of LDL and to estimate the performance in the expected propagation environment
- Methodology
  - Develop physical layer model of technology
  - Validate and iterate as required with known results
    - Most standards define the transmitter implementation, but only provide required receiver performance
    - In the case of LDL, the required performance without coding is identical to that of Binary CPFSK, which is outlined in many Digital Communications textbooks
  - Introduce L-Band channel model and assess performance
    - Make recommendations for receiver implementation to overcome effects of the L-Band propagation environment

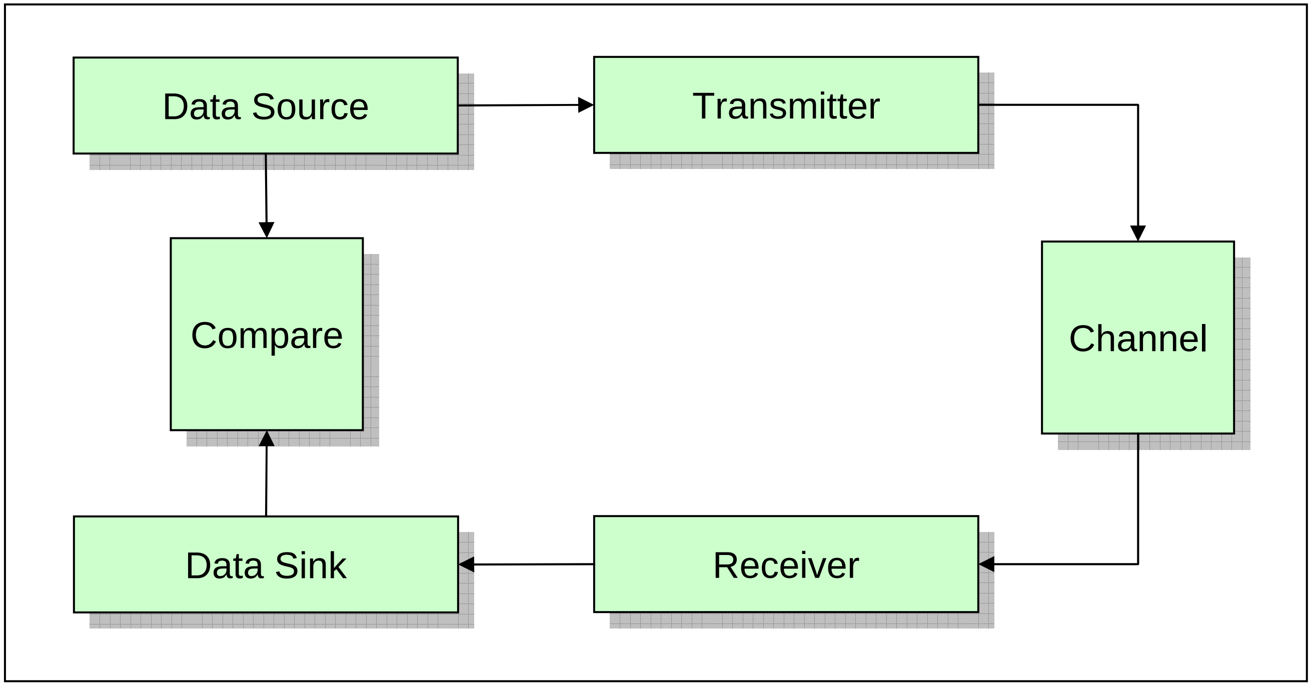
LDL Physical Layer Methodology

- Process for LDL Physical Layer Simulation:
  - Implement L-Band channel model in Simulink®
  - Develop an end-to-end simulation model for LDL and validate the model against published theory
  - Integrate the L-Band channel model with the end-to-end simulation
  - Run the integrated simulation



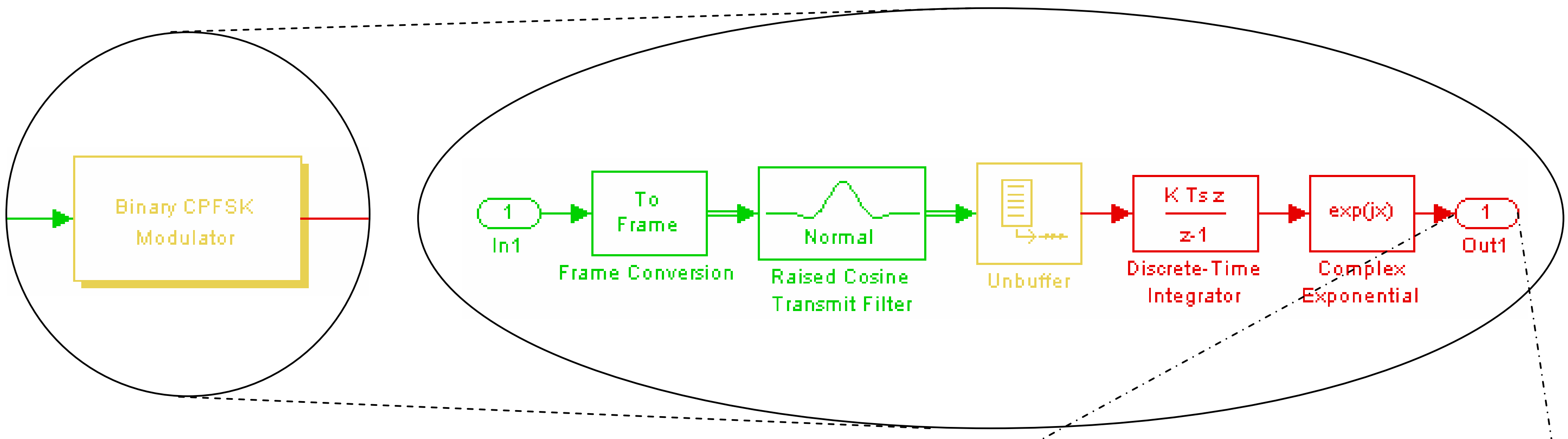
End-to-End Simulation Block Diagram

- An end-to-end physical layer simulation consists of a data source, a transmitter, a channel, a receiver, and a data sink
- The data transmitted is compared to the data received and the Bit Error Rate (BER) is calculated



LDL End-to-End Simulation Development

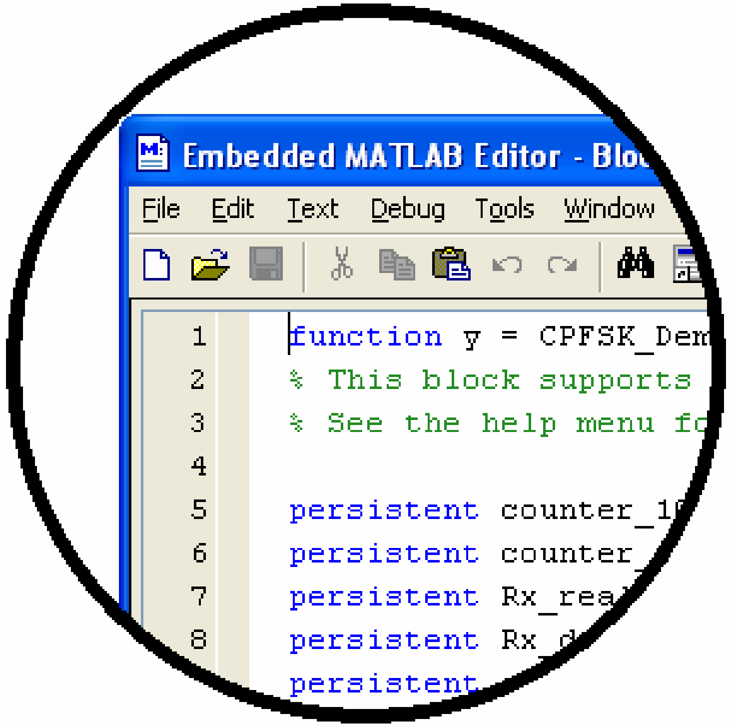
- LDL uses raised cosine pulse-shaping in conjunction with Continuous Phase Frequency Shift Keying (CPFSK) for modulation
- To gain insight into the effects of the different aspects of Binary CPFSK modulation (i.e. – traceback length, pulse length, etc.), the modulator and demodulator were developed as custom models
  - The Binary CPFSK Modulator was implemented as a hierarchical model using native Simulink® blocks as shown

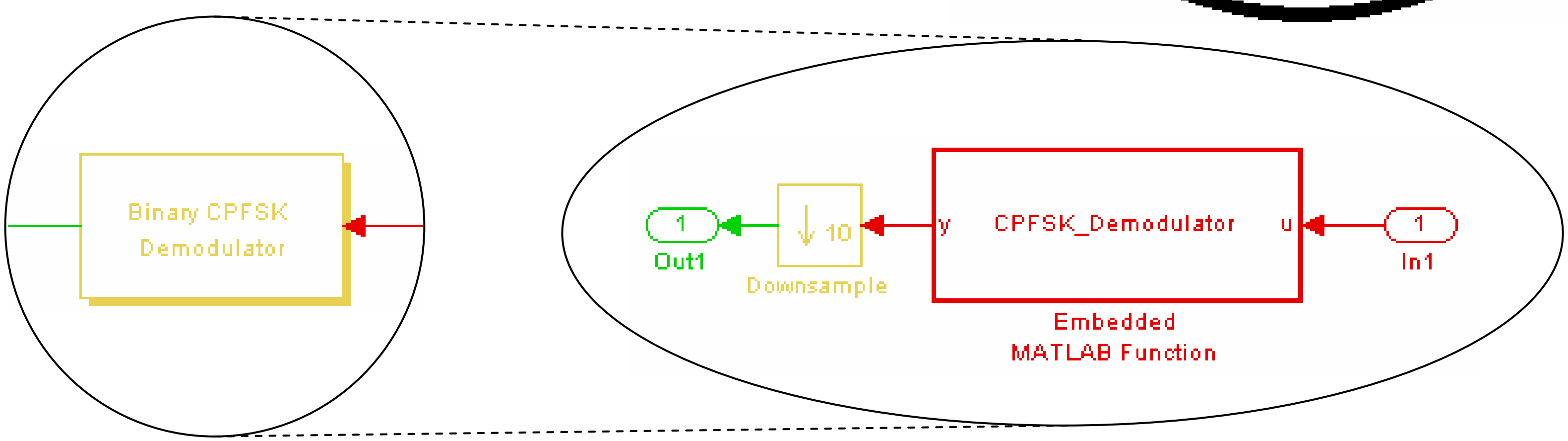


$$v(t) = \sqrt{\frac{2E}{T}} \exp\left\{ j\left[4\pi T f_d \int_{-\infty}^{t} d(\tau) d\tau + \phi_0 \right] \right\}$$

Custom CPFSK Demodulator Implementation

- The binary CPFSK demodulator was implemented using the *Embedded MATLAB Function* block and native downsample block
  - The algorithm for the CPFSK Demodulator was decomposed and coded using the Embedded MATLAB Editor

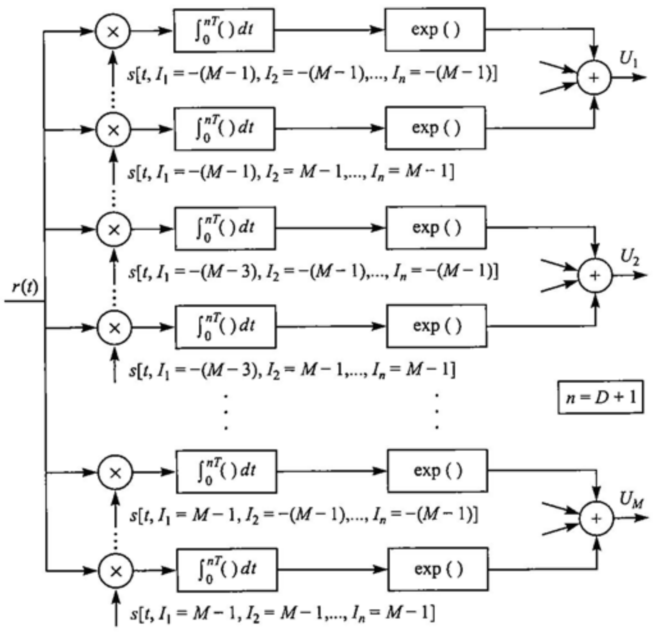




Custom CPFSK Demodulator Algorithm

- The CPFSK demodulator algorithm works as follows:
  - The demodulator uses the history of all previously demodulated symbols up to the current time and appends the sequence with all possible length-n permutations of future symbols
  - This results in 2^n possible sequences for binary symbols (M^n for M-ary)
  - Next, each sequence is cross-correlated with the received signal
  - The middle symbol of the appended sequence with the highest cross-correlation value is chosen as the demodulated symbol
- A full discussion of the demodulator algorithm can be found in Section 5.3.3 of Proakis' *Digital Communications*

Block diagram of demodulator for detection of CPFSK

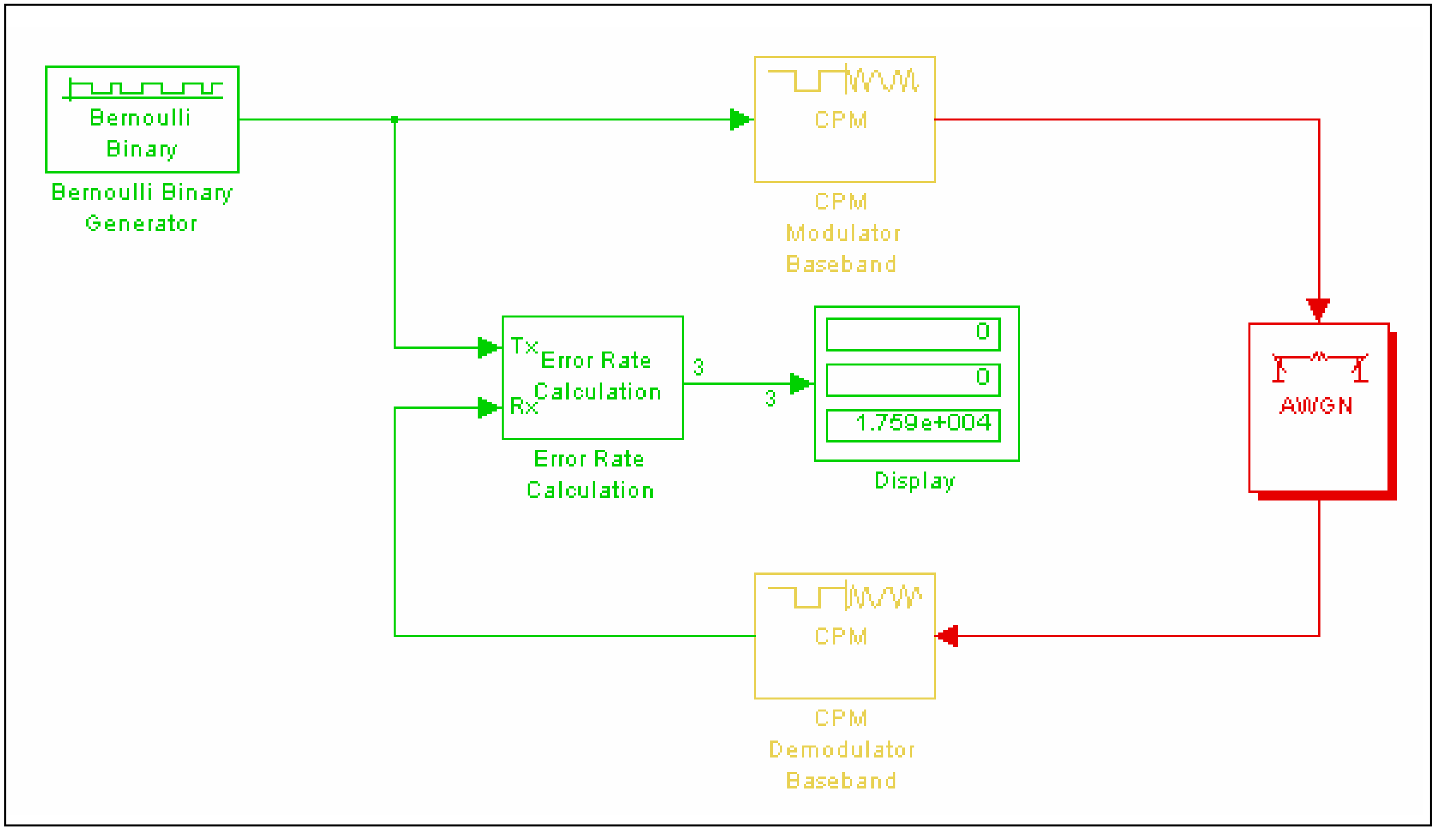


Custom Demodulator/ Receiver Performance

- During validation simulations two deficiencies were acknowledged in the custom-coded demodulator
  - The custom demodulator has a 1-2 dB implementation loss
  - The custom demodulator runs very slowly
- To speed up the simulation runtime, we replaced our custom implementation with native Simulink CPM blocks to perform the Modulator/Demodulator functionality

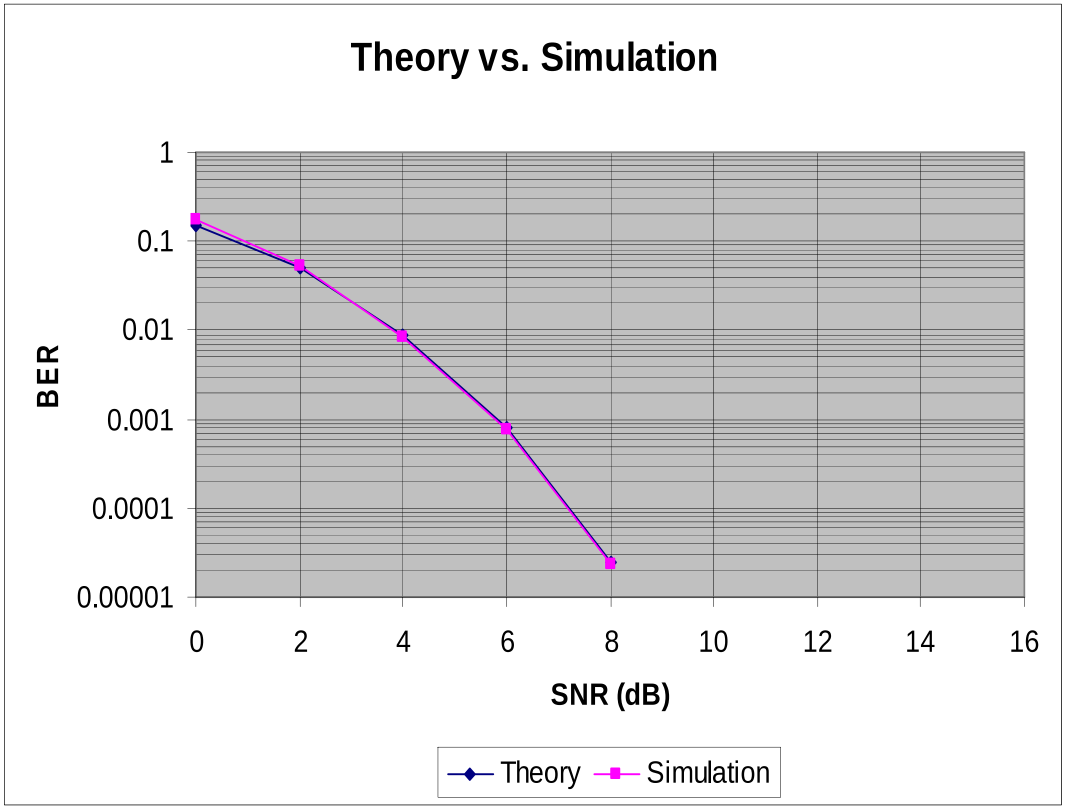
End-to-End Simulation

- The end-to-end simulation with an AWGN channel is illustrated in the diagram below



Simulation Validation

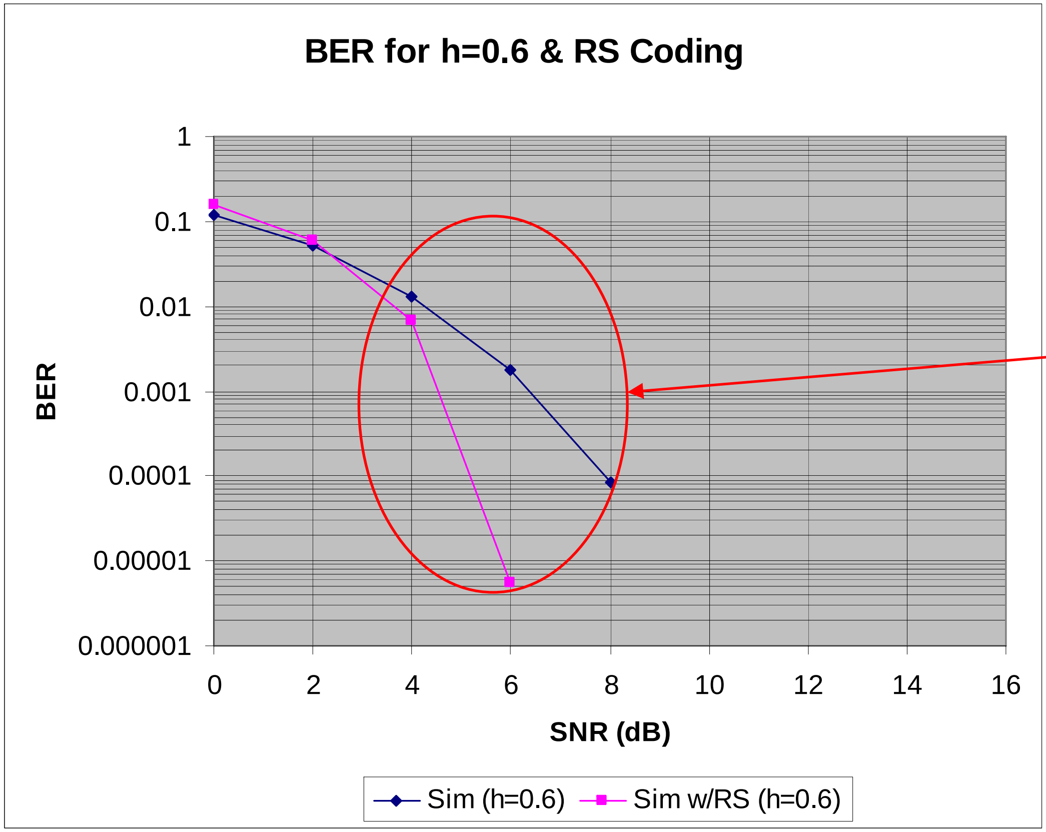
- To validate our simulation we compare BER curves
  - The theoretical curve is the performance of binary CPFSK with coherent detection using n = 5, and h = 0.715 [Proakis]
  - Our model uses the same traceback length (n = 5) and modulation index (h = 0.715)



Using a modulation of 0.715 minimizes probability of error for binary CPFSK [Schonhoff 1976]

Simulation with Reed-Solomon Coding

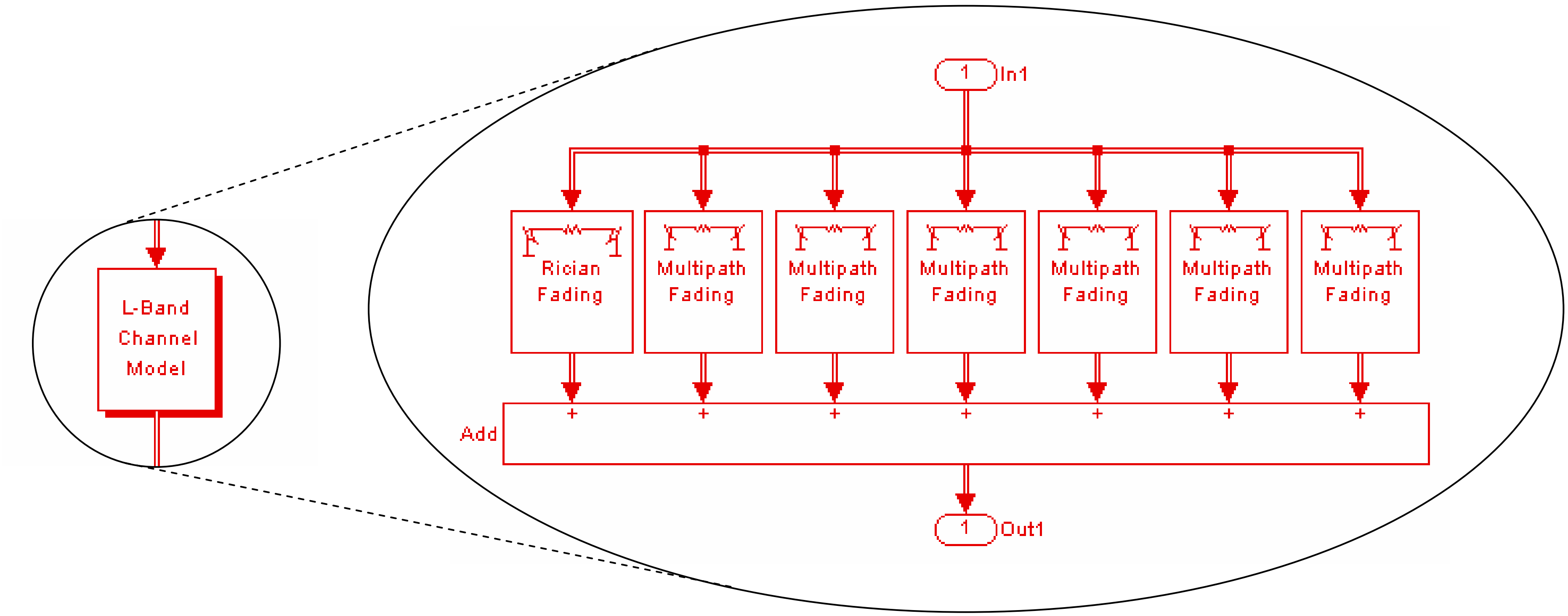
- A modulation index of 0.715 was required to validate the model with published results, but LDL calls for a modulation index of 0.6
  - Changing the modulation index from 0.715 to 0.6 pushes the BER curve out ~1 dB
  - The Reed-Solomon (72,62) code provides a coding gain of 3-4 dB in the expected region of operation



In order for the RS code to provide a substantial coding gain, the raw BER must be less than 10^{-2}

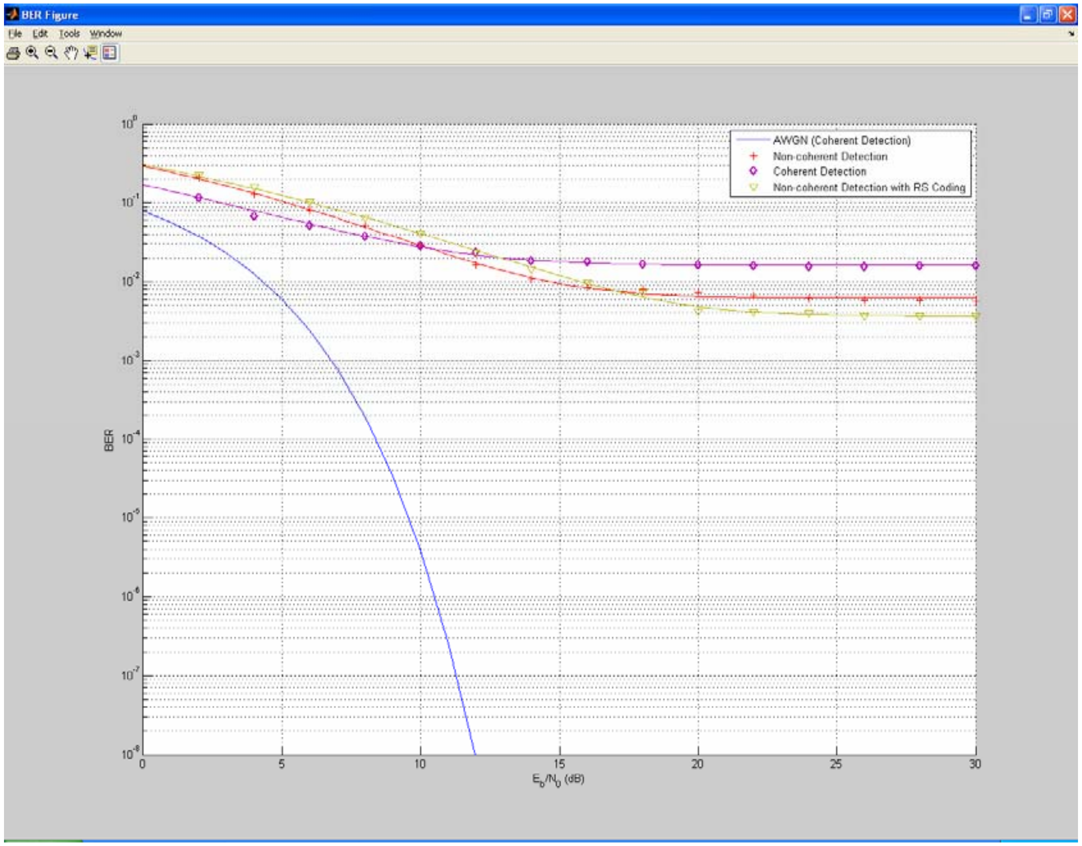
L-Band Channel Model Implementation

- After validating the end-to-end simulation model, the L-Band Channel Model was integrated into the simulation
- The L-Band channel model was implemented as a hierarchical model using native Simulink® blocks



BER with Channel Model

- The plot below shows the system performance of LDL in the presence both AWGN and the L-Band Channel Model
  – Both coherent and non-coherent detection schemes are shown
  – Non-coherent detection has superior performance, but needs equalization



Conclusions

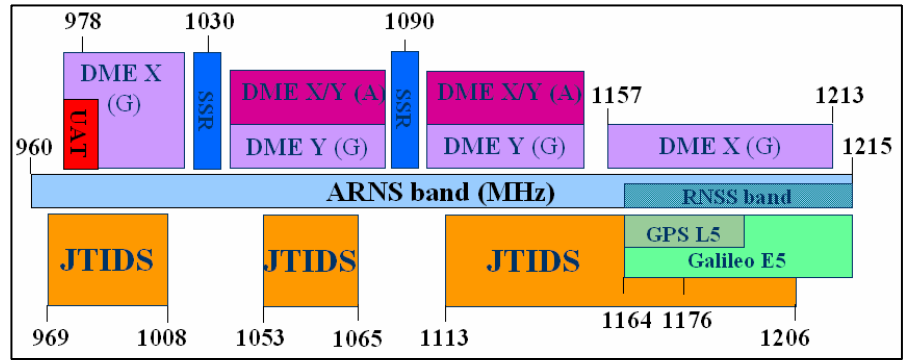
- The LDL channel model is a conservative model that introduces an irreducible error floor to system performance, which is consistent with a frequency-selective channel theory
- Based on the results of this model, LDL will require channel equalization to mitigate the effects of the Air/Ground Aeronautical Channel in L-Band
- The LDL simulation was run using a data rate of 62.5 kbps
  - LDL documentation states that other data rates (i.e. – 83.3 kbps, 100 kbps, etc.) might work well for LDL, but at these higher data rates, further degradation of system performance is expected
- These are initial results and are still being validated

Interference Modeling Overview

Background - L-Band Utilization

- 960-1215 MHz band has a primary allocation for Aeronautical Radio-Navigation Services (ARNS)
  - ICAO standardized systems that use spectrum in this band are
    - Universal Access Transceiver (UAT)
    - Secondary-Surveillance Radars (ATCRBS Mode A and C, Mode S)
    - Distance Measuring Equipment (DME)
    - Spectrum allocations are standardized by ICAO; however, some DME allocations are defined on a national basis between 962 and 977 MHz
  - Military Systems
    - TACAN
    - JTIDS/MIDS (Link 16)
    - Use is subject to national coordination between military and civil authorities
  - Global Navigation Satellite Systems
    - Upper part of the band that has been designated for the Radio-Navigation Satellite Service (RNSS)

Current and Planned L-Band Utilization



Note: Graphic taken from ICAO paper, “Interference susceptibilities of Systems Operating in the 960-1215 MHz Band Application to the Compatibility Analysis of the Future Communication System “, ACP-WGF14/WP12

Background – Analysis Methodology Generic Process

- A generic process for interference analysis would have the following elements:
  - Describe the source of interference and the interference mechanism
    - Description is usually in the form of power spectrum and time characteristics (e.g., Tx power, Transmission bandwidth, duty cycle)
  - Quantify the isolation between transmitter output and receiver input
    - This isolation includes the effects of antenna gains, cabling losses and propagation
  - Determine the ratio of undesired to desired signal power at the input of the receiver decision process (detector)
  - Quantify receiver performance as a function of this D/U ratio, ascribe a required performance and assess compatibility
- The last item is shaded red because it is the difficult element of the process and the focus of the simulation work that was conducted

Background – Task Objective and Approach

- Objective
  - During the consensus FAA, NASA and ITT deliberations in June two technologies were selected for analysis
    - LDL and P34 were selected as being representative of the recommended technologies being proposed as the FRS
    - It was determined that compatibility of these proposed systems with existing ICAO standardized civil aviation systems would be assessed
  - The objective of this task is to determine the compatibility of P34 and LDL with ICAO standardized civil aviation systems
- Approach
  - For each system being analyzed
    - Select an appropriate measure of interference degradation
    - Collect information about the system (known susceptibilities, system technical parameters)
    - Develop physical layer system model and validate with known results
    - Introduce interference source and predict victim performance

Background – Prioritizing Analysis Resources

Interference Source	Victim Receiver	Interference Mechanisms	Source Characterization	Has Vulnerability been characterized?
FRS 960 – 1024 MHz 960 – 977 MHz preferred	GNSS 1176.45 MHz	Broadband Noise Spurious Emissions Desensitization	Noise (WB) NB or CW	Yes Yes
	Mode S 1030 MHz 1090 MHz	Broadband Noise Spurious Emissions Desensitization	Noise (WB) NB or CW	Yes Unknown
	UAT 978 MHz	Adjacent Signal Broadband Noise Spurious Emissions	FRS Dependent Noise (WB) NB or CW	No Yes Yes
	DME 962 – 1019 MHz	Co-channel Adjacent Signal Broadband Noise Spurious Emissions	FRS Dependent FRS Dependent Noise (WB) NB or CW	No No Yes Yes

DME Modeling

DME Overview

- The Distance Measuring Equipment (DME) system is an ICAO standardized navigational aid used to determine aircraft location
- The DME system consists of an interrogator located on board the aircraft and a transponder located at the ground station
  - At regularly spaced intervals, the interrogator transmits a coded pulse to the transponder
  - Reception of this pulse triggers a coded reply from the interrogator at a different frequency
- The DME system uses the principle of elapsed time measurement between these two messages as the basis for determining the distance between the aircraft and the ground station, also called the *slant range distance*
- DME frequencies are spaced in 1 MHz increments throughout the 962-1213 MHz band, providing potential for interference to and from FRS in L-Band

DME Known Susceptibilities

Airborne DME Receiver	On-ground DME Receiver
Co-channel DME signal (1/2) (same frequency and same pulse pair spacing). Accuracy requirements shall be met in presence of 3600 ppps with a minimum C/I = 8 dB (annex 10, Vol. I, section 3.5.5.3.4.1 & EUROCAE ED-54) **Co-channel DME signal (2/2)** (same frequency and different pulse pair spacing). Accuracy requirements shall be met in presence of 3600 ppps with a minimum C/I = -42 dB (EUROCAE ED-54)	**Co-channel DME signal** Not known
Continuous Wave signal (CW) Sensitivity requirement shall be met for: •In-band continuous CW up to -99 dBm •Out-of-band CW up to -40 dBm (EUROCAE ED-54)	**Continuous Wave signal (CW)** Reply efficiency shall remain greater than 70% in presence of in-band continuous CW with a minimum C/I = 10 dB. (EUROCAE ED-57)
JTIDS/MIDS signal Maximum value of -36 dBm at the antenna port based on time-to-acquire requirement. Time slot duty factor (100/50) and minimum vertical separation of 1000 ft. Experimentally verified as part of NATO Common Frequency Clearance Agreement.	**JTIDS/MIDS signal** Tolerated up to -33 dBm at the antenna port based on time-to-acquire requirement. Time slot duty factor (100/50). Experimentally verified as part of NATO Common Frequency Clearance Agreement.
Broadband Interference Maximum value of -99 dBm/MHz within receiver bandwidth based on sensitivity requirement as for the CW case. (Rec. ITU-R M.1639)	**Broadband Interference** Not known

DME Known Susceptibilities – RNSS Emissions

- ITU Document 8D/107-E presents the results of measurements that characterize the susceptibility of DME Interrogator-Receiver Avionics to RNSS emissions
- Measurements are made for CW (as a baseline) as well as the RNSS C/A and P-codes
  - Note that despite the huge difference in signal bandwidths (fully 10 dB), the susceptibility to the C/A and P-codes only differs by 2 dB
    - Same effect for ASOP and BSOP
    - ASOP is more sensitive
    - Results are hard to conceptualize

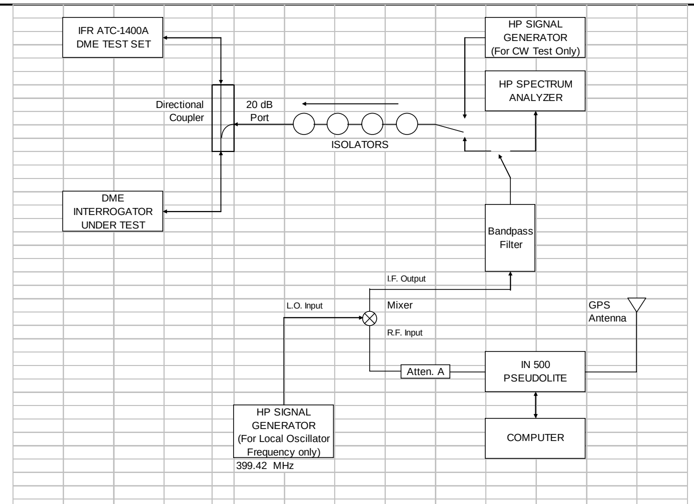


FIGURE 1. TEST SETUP

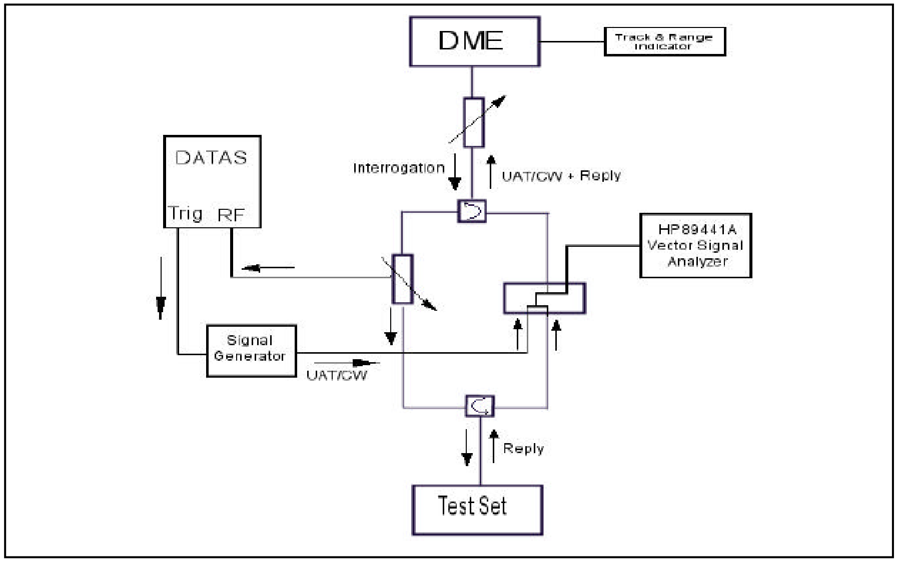
Desired DME Signal Level	DME Frequency	Interference level dBm					
		CW		RNSS C/A Code		RNSS P Code	
dBm	MHz	ASOP	BSOP	ASOP	BSOP	ASOP	BSOP
-83	1176	-89	-87	-91	-90	-89	-88

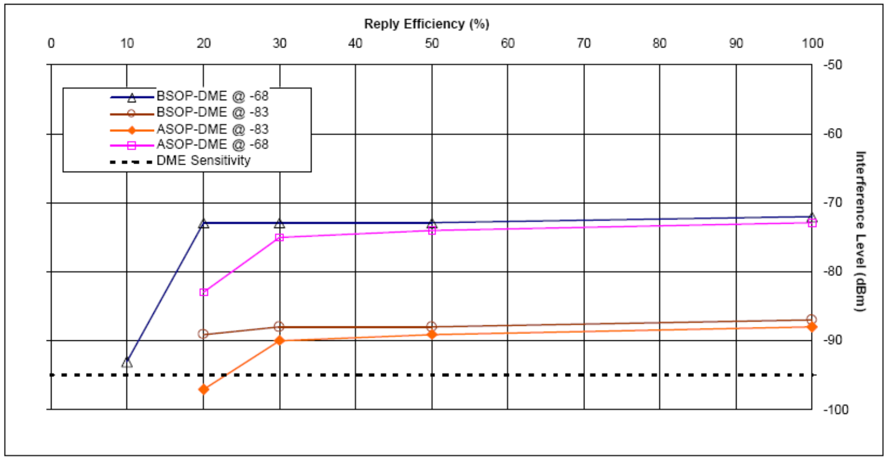
DME Receiver Modeling

- Obtained published data on DME interference from GPS signals
  - The data indicates that interference from P(Y) and from C/A signals does not differ much, even though the P(Y) signal has 10 times larger bandwidth. Developed a hypothesis, which assumes that pulse detection in DME equipment is performed over a short window on the order of one P(Y) chip length. Computed the receiver window length, which would yielded a match with the published data.
- Assumed a DME architecture, as follows:
  - A unit sends an interrogation pulse pair and then checks for return pulse pairs over multiple short time windows. A pulse pair is detected if the signal level is above some threshold at the expected pulse arrival times, below the threshold between pulses
  - If a return pulse pair is detected, *N* more interrogation pulses are sent. A lock is detected if at least *n* return pulses are detected
  - A lock is lost if the fraction of detected pulses falls below a threshold
  - If the return pulse pair was not detected after the first interrogation pulse, the process is repeated up to *k* times
- Built a mathematical model, which describes this architecture, and ran it for different values of parameters, and determined sets of parameters that match published results

DME Known Susceptibilities – UAT Measurements to DME Receivers

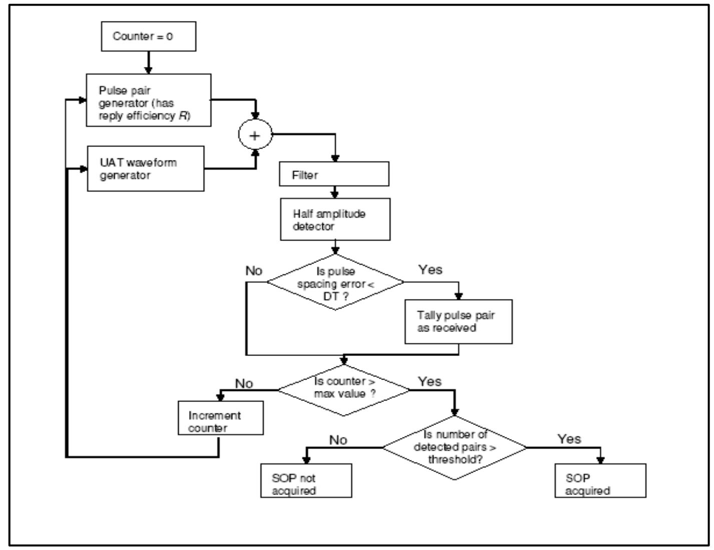
- The FAA technical center has made measurements of UAT interference effects on DME interrogators
  - Test setup is shown in the top right picture
  - Measurement results are shown in the bottom right
- Testing on three different DME interrogators
  - Bendix King KD-7000
  - NARCO DME-890
  - Honeywell KDM-706A
- Degradation measure selected was ASOP & BSOP
  - ASOP – Acquire Stable Operating Point
  - BSOP – Break Stable Operating Point

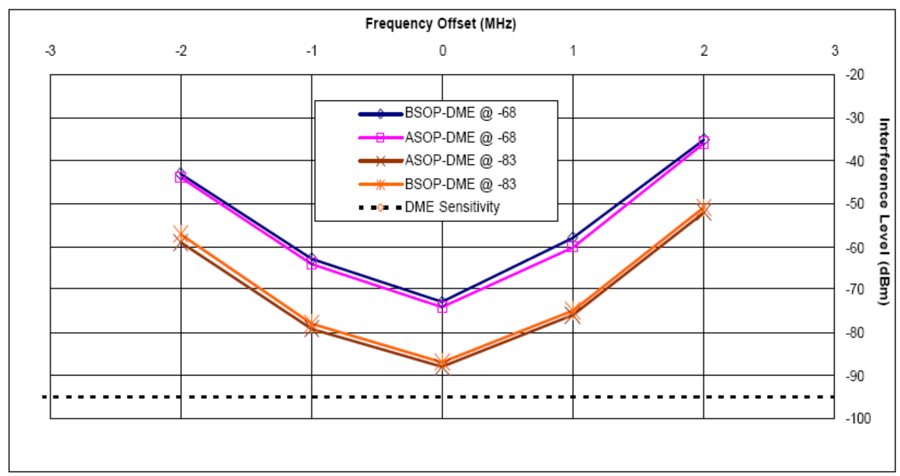




DME Receiver Modeling

- Implemented a model for interference from UAT
- The model is as follows:
  - DME pulses are modeled as Gaussian
  - UAT interference is modeled as frequency-shift keying, constant amplitude signal
  - DME pulses and interference are superimposed in time domain
  - The resulting signal is filtered using a filter with Gaussian response function. The width of the filter response is computed to match a measured decrease of interference effect at frequency offset of 1 MHz as compared to no offset

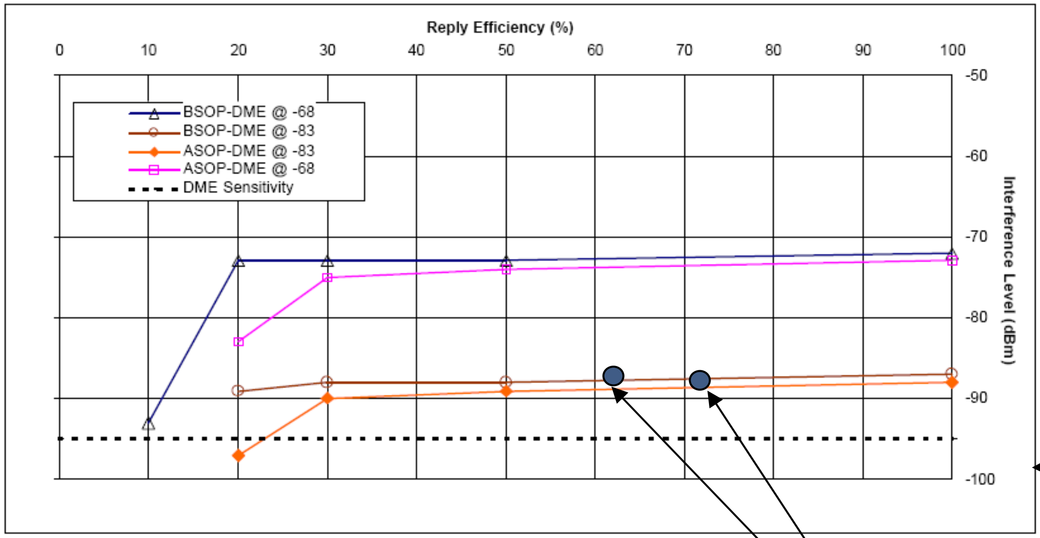




DME Receiver Modeling (Continued)

- For each filtered pulse, the DME airborne receiver determines the half-amplitude point with respect to the pulse amplitude. The amplitude of a particular pulse may differ from the average amplitude due to interference; however, the half-amplitude point is defined as the timing of the half-amplitude of the average pulse (which is the same as the amplitude of a pulse without interference)
- For each pulse pair to be received, the half-amplitude timing of two pulses must be separated by the time interval, which is close to 12.5 microseconds. If the measured time separation differs from the nominal value by more than some aperture DT, the pair is tallied as one not received
- To acquire lock, there is some minimum percentage of pairs received *A_min*
- To maintain lock, there also is some minimum percentage of pairs received *B_min*
- There is hysteresis in acquisition and maintaining of lock

DME Receiver Modeling - Results



Measured results for Bendix King KD-7000 with simulation results superimposed

Simulation Parameters

DME power (dBm)	Unit modeled	Interference at 1 MHz offset vs. 0 offset	Aperture DT, micro-seconds	UAT power (dBm)	Percent of pairs received
-83	Bendix King KD-7000	12	3.0	-88.0	61 % BSOP
-83		12		-89.0	73 % ASOP
-83	Honeywell KDM-706A	20	0.7	-95.0	62 % BSOP
-83		20		-96.0	70 % ASOP

DME Receiver Modeling - Discussion

- Despite the seemingly good correlation of results to the developed model on the previous slide, several problems with the developed model were noted during validation testing
  - The measured results are extremely flat over the reply efficiency range of the test
    - Indicative of an AGC circuit (perhaps) or some second order effect that isn't immediately obvious
  - To create a range of "Acquire Locks" for various reply efficiencies, the interference power for our model had to be varied over a 10 – 12 dB range
    - This was deemed to be sufficiently far from measured results as to be a non-reliable indicator (for use in predicting interference from FRS sources)
  - Several requests for information and assistance were made by our NASA sponsor, but the information that was needed (detailed algorithm descriptions from radio manufacturers) was not made available
- A decision was made to not further use the developed model
- Measurements are recommended in Phase III to more substantively characterize the DME to communication waveforms
  - More discussion on this will be provided in Briefing #9

Universal Access Transceiver Modeling

UAT Overview

- UAT is a wideband data link that enhances pilot situation awareness and increases safety by allowing general aviation pilots to process navigational signals from the Global Positioning System (GPS), receive traffic information, broadcast their positions, and perform other functions

- The Universal Access Transceiver (UAT) is a technology that is standardized through ICAO for ADS-B, TIS-B and FIS-B applications

- UAT operates at 978 MHz, providing potential for interference to and from a FRS in L-Band

UAT Known Susceptibilities

- DME signal interference (Basic & high performance receivers)
  - 99% successful message reception of long messages in presence of DME pulse pairs at a nominal rate of 3600 ppps at either 12 or 30 us spacing at a level of -30 dBm for any 1 MHz channel frequency between 980 MHz and 1215 MHz (desired signal >= -90 dBm)
- DME signal interference (Basic receivers only)
  - 90% successful message reception of long messages in presence of DME pulse pairs at a nominal rate of 3600 ppps at either 12 or 30 us spacing at a level of -56 dBm for any 1 MHz channel frequency between 979 MHz (desired signal >= -87 dBm)
- DME signal interference (High performance receivers only)
  - 90% successful message reception of long messages in presence of DME pulse pairs at a nominal rate of 3600 ppps at either 12 or 30 us spacing at a level of -43 dBm for any 1 MHz channel frequency between 979 MHz (desired signal >= -87 dBm)

UAT Interference Analysis Overview

- The objective of this task was to characterize the impact of LDL and P34 interference on UAT performance
- Assumptions
  - UAT
    - The basic ADS-B message code RS(30,18) has been modeled
    - The analysis does not include long ADS-B message codes RS(48,34) or Ground Uplink Message Codes RS(92,72)
  - LDL
    - The LDL transmitter model uses a data rate of 62.5 kbps
    - The analysis does not consider data rates of 83.3 kbps or 100 kbps
  - P34
    - 50 kHz configuration of P34 was modeled
    - The analysis does not consider 100 kHz or 150 kHz configurations

UAT Interference Analysis Approach

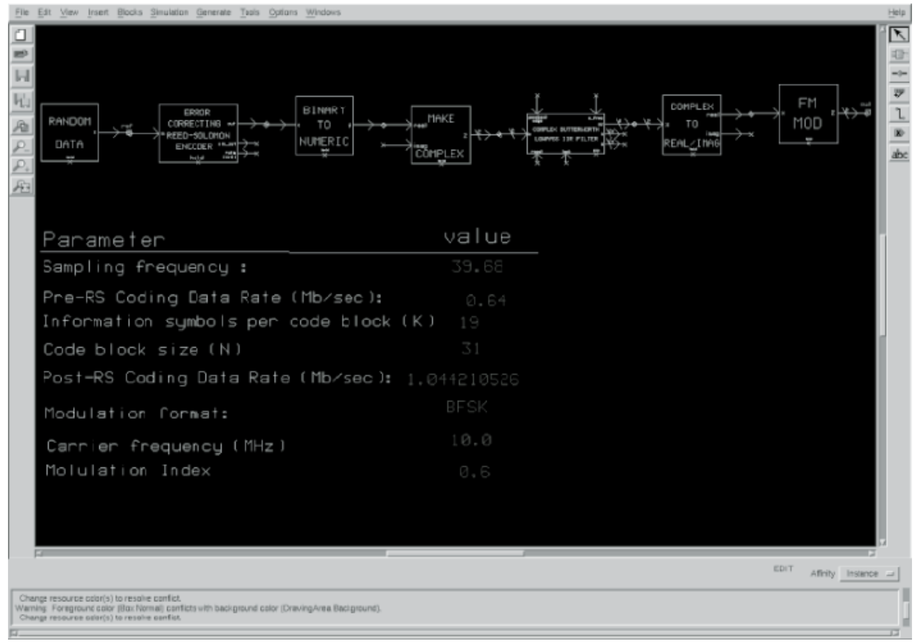
- The process for analyzing UAT interference is as follows:
  1. Develop UAT end-to-end simulation model using Signal Processing Worksystem (SPW)
  2. Validate performance of UAT model against published results for BFSK
  3. Integrate Reed Solomon coding into the end-to-end simulation model
  4. Validate performance of UAT model with RS coding against published results for coded BFSK
  5. Develop LDL transmitter model and validate PSD
  6. Develop P34 transmitter model and validate PSD
  7. Integrate LDL and P34 interferer models into UAT end-to-end simulation model
  8. Collect and analyze performance data (BER curves) for varying degrees of interference

UAT Transmitter Model

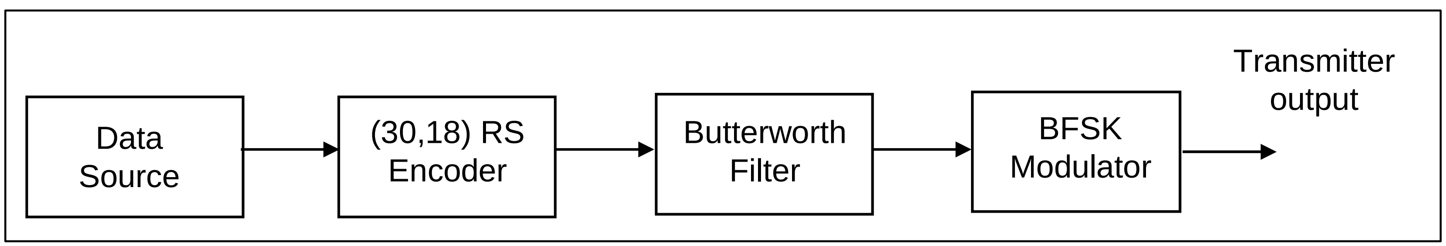
Parameter	Value
Modulation Data Rate	1.05 Mb/sec
Coding	(30,18) Reed-Solomon(1)
Baseband Filter	3rd Order Butterworth
Modulation	BFSK (Modulation index = 0.6)

Notes:
1. Actual simulation model uses a (31,19) RS which should have nearly identical performance as the (30,18), however, without the added simulation complexity of a punctured code

UAT Parameters Used for Analysis



SPW Implementation of UAT Transmitter

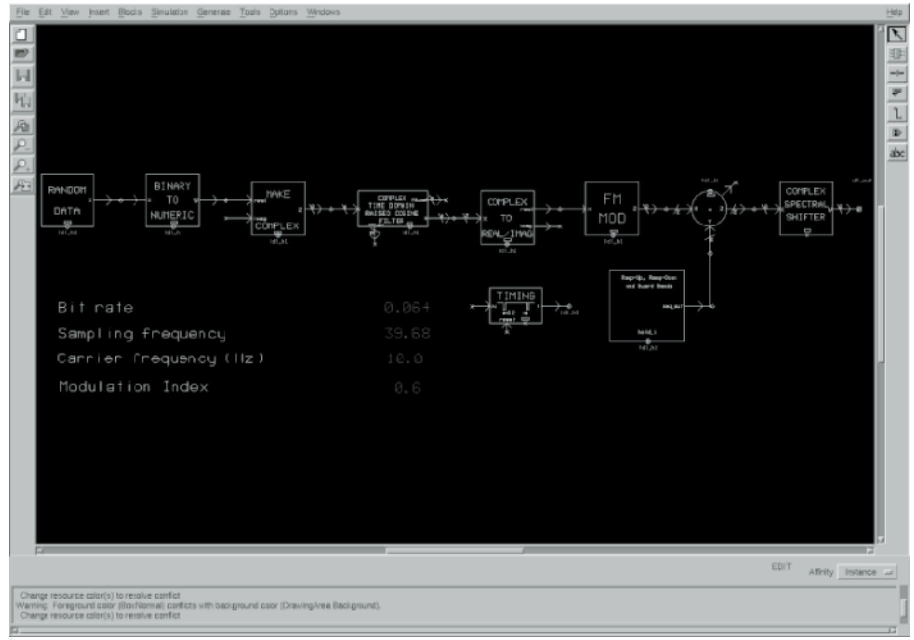


UAT Transmitter Block Diagram

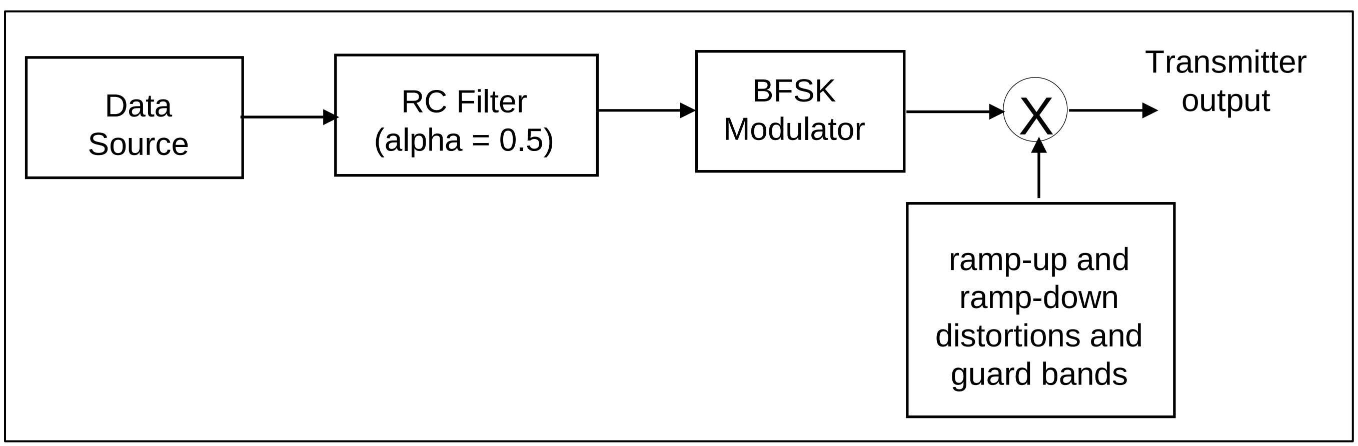
LDL Transmitter Model

Parameter	Value
Data Rate	62.5 kb/sec
Baseband Filter	RC (alpha = 0.5)
Modulation	BFSK (Modulation index = 0.6)

LDL Parameters Used for Analysis



SPW Implementation of LDL Transmitter



LDL Transmitter Block Diagram

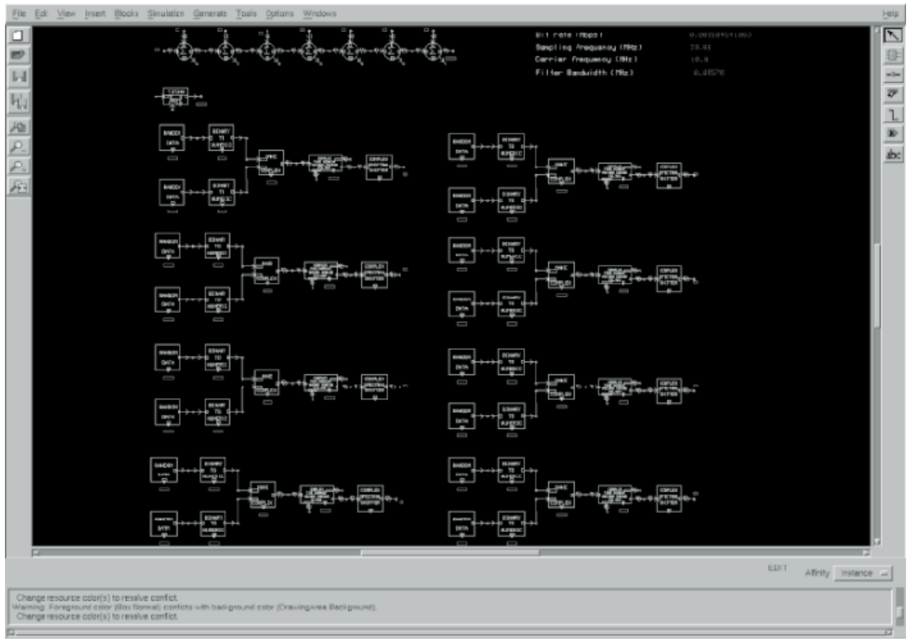
P34 Transmitter Model

Parameter	Value
RF Subchannels	8 (1, 2)
Subchannel Spacing	5.4 kHz
Symbol Rate	4.8 kb/sec
Baseband Filter	SRRC (alpha = 0.2)
Modulation	QPSK

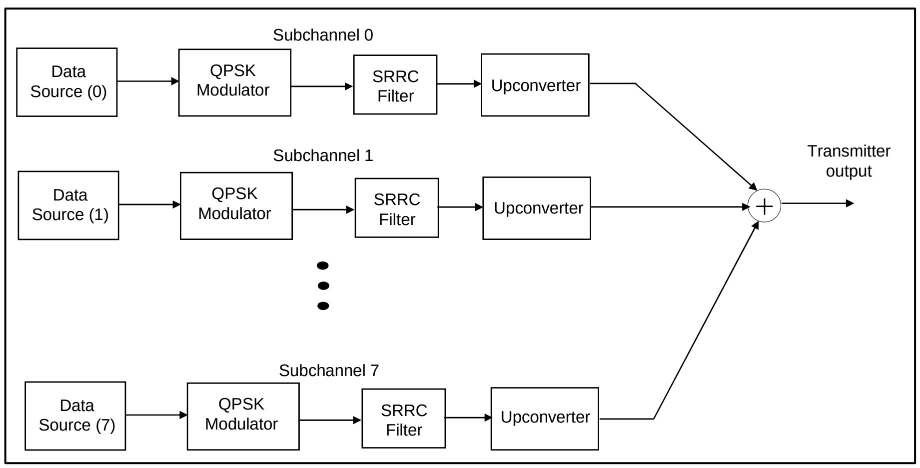
Notes:

1. 50 kHz channel configuration
2. Subchannel center offset frequencies are -18.9 kHz, -13.5 kHz, -8.1 kHz, -2.7 kHz, +2.7 kHz +8.1 kHz, +13.5 kHz, +18.9 kHz

P34 Parameters Used for Analysis



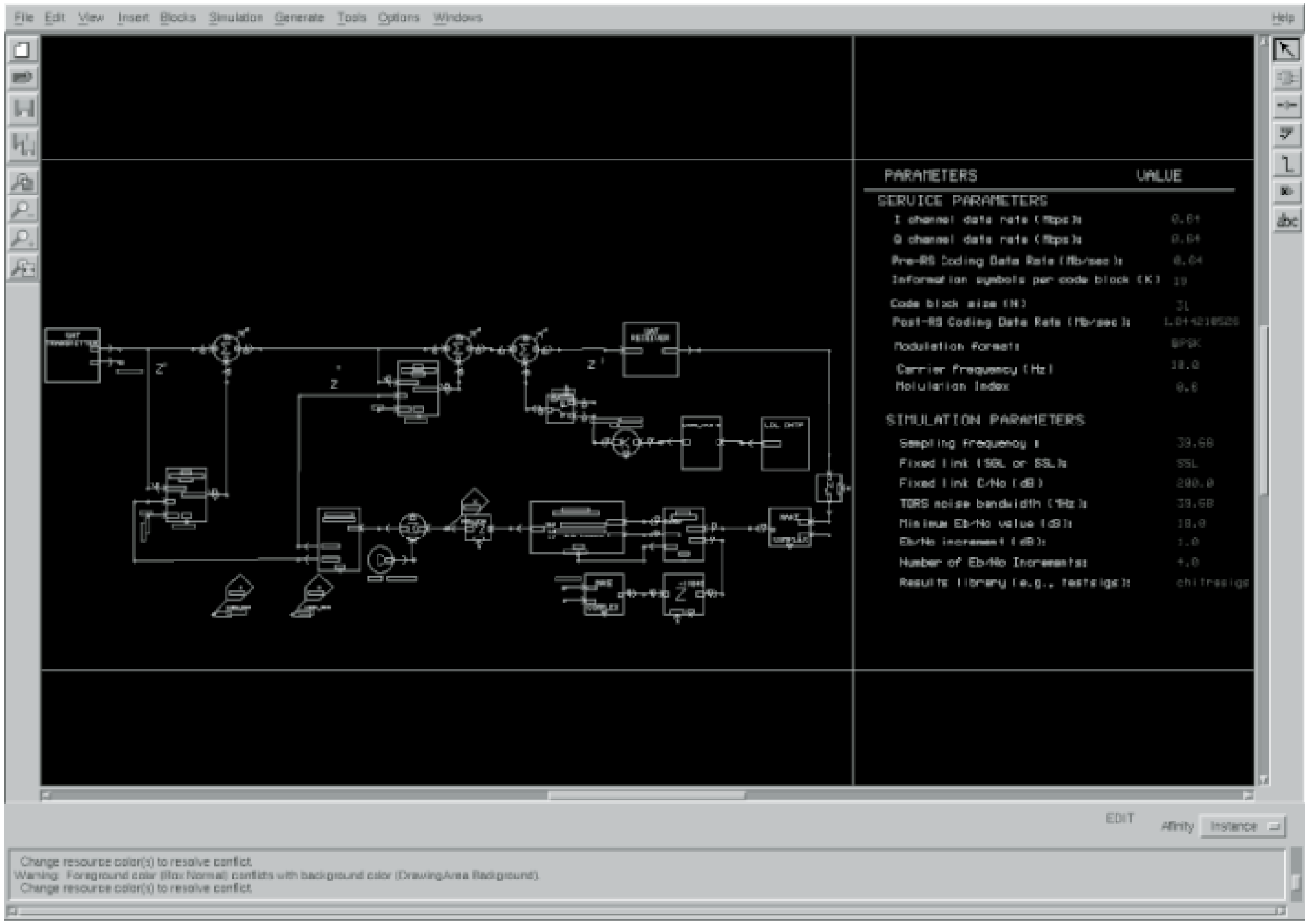
SPW Implementation of P34 Transmitter



P34 Transmitter Block Diagram

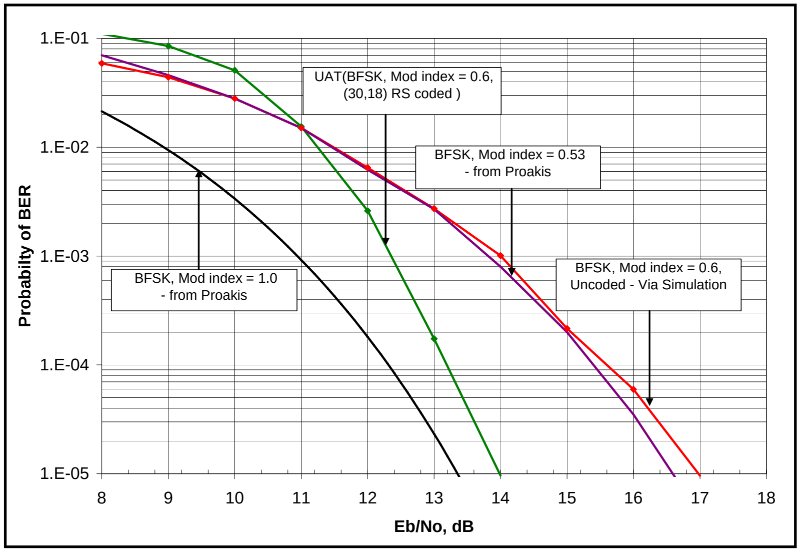
UAT End-to-End Simulation Model Implementation

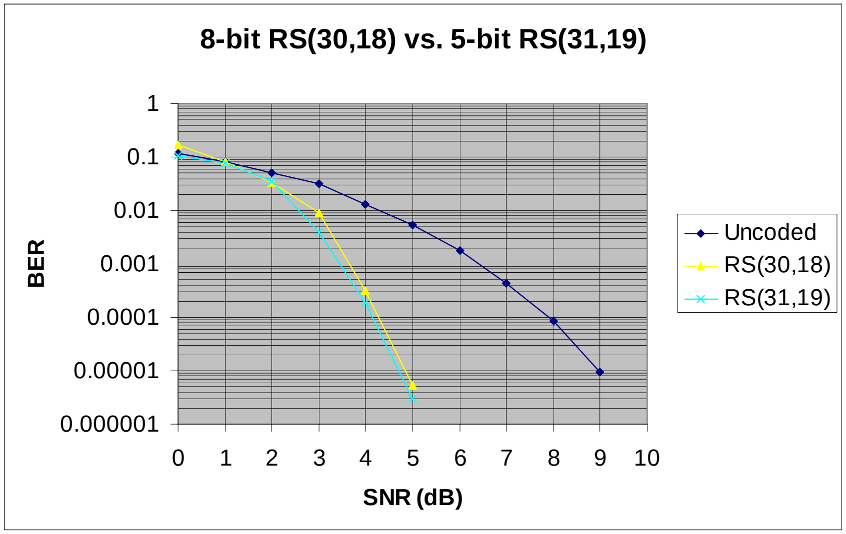
- The following diagram provides a snapshot of the actual UAT end-to-end simulation model



Validation of the Model - UAT Performance in AWGN

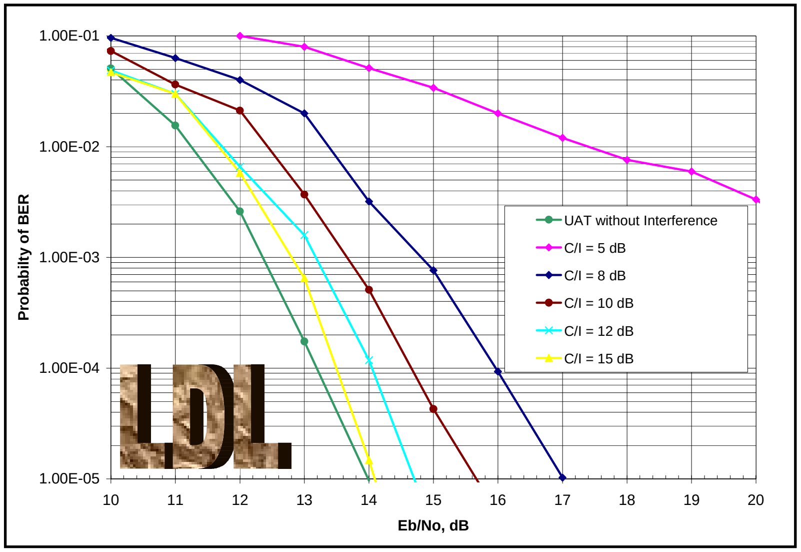
- To assess the validity of the developed model, simulations were run end-to-end with only AWGN degradation
  - Results are compared (favorably) to theory in the top most chart
- To validate the assumption of a native 5-bit Reed Solomon code (instead of the punctured 8-bit code that is defined for the UAT), a simulation was developed in Simulink
  - Punctured coding is very difficult using SPW but trivial in Simulink
  - The bottom most chart shows good agreement between the two codes
  - It is understood that the integrity of the codes differ, but that information was not leveraged in this analysis

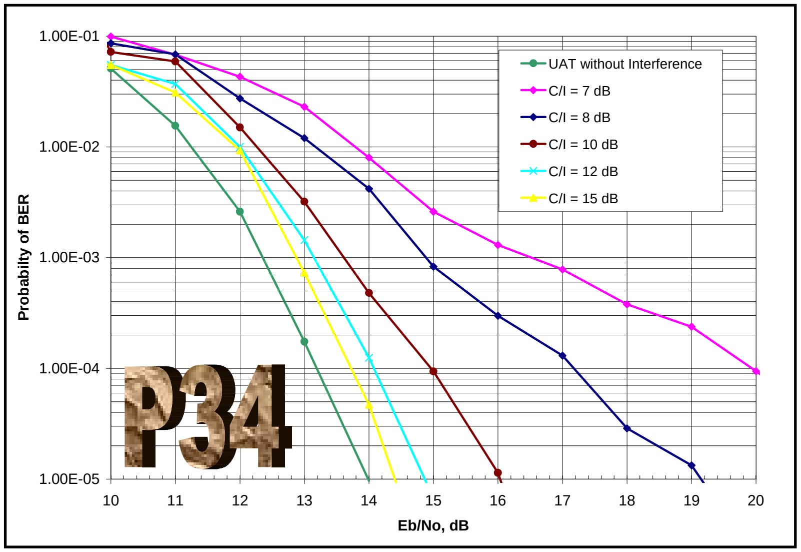




Results – UAT Performance in the Presence of LDL or P34

- The top chart provides a collection of BER curves for varying degrees of LDL Interference into UAT signal
- The bottom chart provides a collection of BER curves for varying degrees of P34 Interference into UAT signals
- From the curves, it would appear that a C/I ratio between 12 and 15 dB is required for minimum degradation to the UAT receiver
- LDL has slightly better performance than P34 in terms of not interfering with UAT receivers





Mode S Modeling

Mode S Overview

- Mode Select (Mode S) is a system developed to phase out the Air Traffic Control Radar Beacon System (ATCRBS) by providing enhanced surveillance information for use by Air Traffic Control automation
- Mode S provides more accurate position information and minimizes interference by discreet interrogation of each aircraft
  - Each aircraft has its own unique mode S address, providing a mechanism by which an aircraft can be selected/interrogated such that no other aircraft reply
- Mode S also provides a digital data link to exchange information between aircraft and various ATC functions and weather databases
- Mode S operates at 1030 and 1090 MHz providing a potential for interference to and from a FRS in L-Band

Mode S Interference Analysis Approach

- Developed Mode S transmitter simulation model
    - Exactly meets the rise-time, decay-time and PSD mask requirements given in Mode S MOPS
    - Simulation model further calibrated against Mode S waveforms given in Mode S MOPS
  - Developed Mode S preamble detection circuit simulation model
    - Makes a hard decision on every 0.5 Microsecond symbol
    - Selectable sensitivity included in model
- Developed Mode S end-to-end simulation model using developed Mode S transmitter and preamble detection model
- Integrated LDL and P34 interferer models into Mode S end-to-end simulation model

Mode S Signal Characteristics

- Per Reference [1], Mode S signal characteristics are assumed as follows:

Parameter	Value
Preamble Length	8.0 Microsec
Data Block Length	112.0 Microsec
Parity Check Bits	On AP field (24 bits)
Data Rate	1 Mb/sec
Modulation	Pulse - Position Modulation
Filter	Gaussian (1)

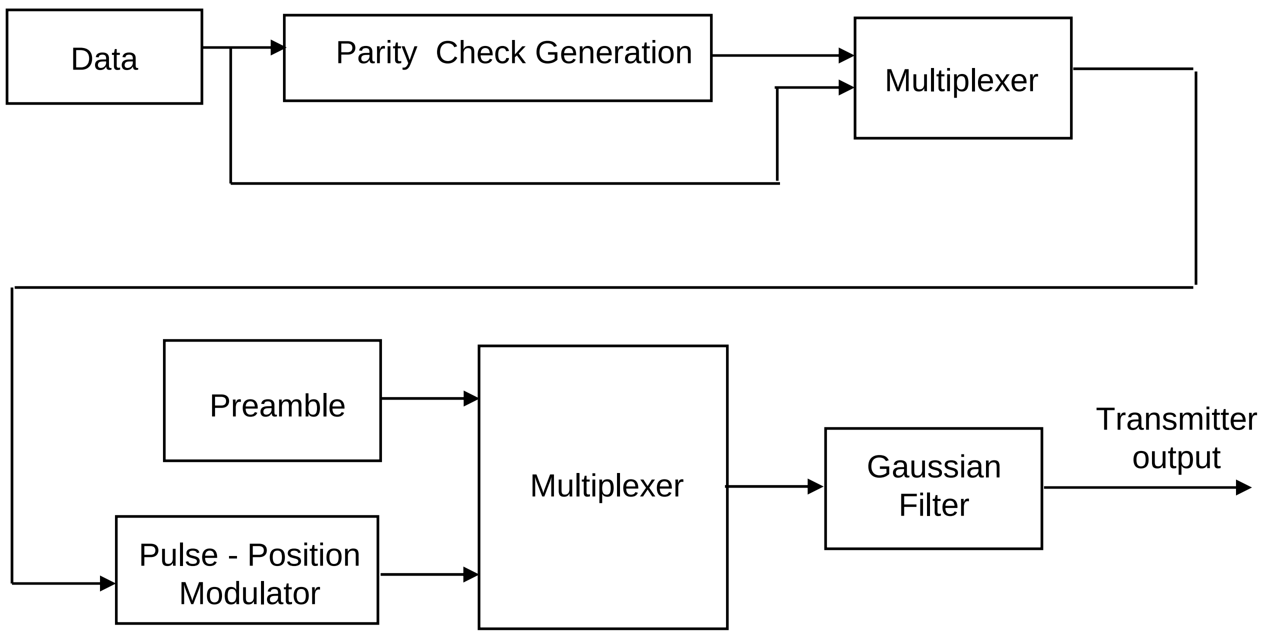
Notes:

1. Bandwidth assumed to meet the rise-time decay-time and PSD mask requirements given in Reference [1]

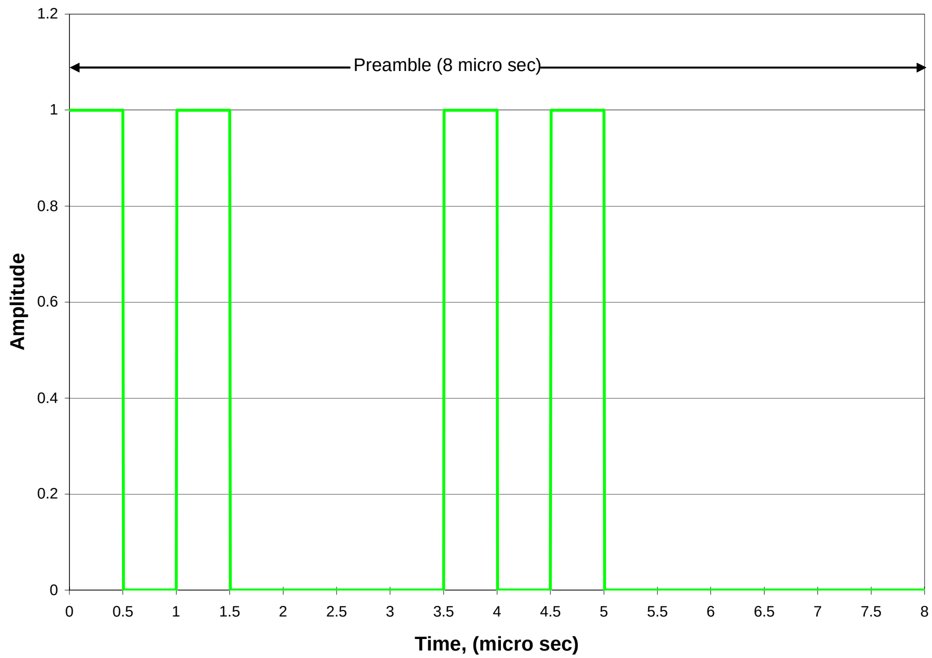
- [1] "MOPS for 1090 MHz Extended Squitter Automatic Dependent Surveillance - Broadcast (ADS-B) and Traffic Information Services - Broadcast (TIS-B), Volume 1" by RTCA DO-260

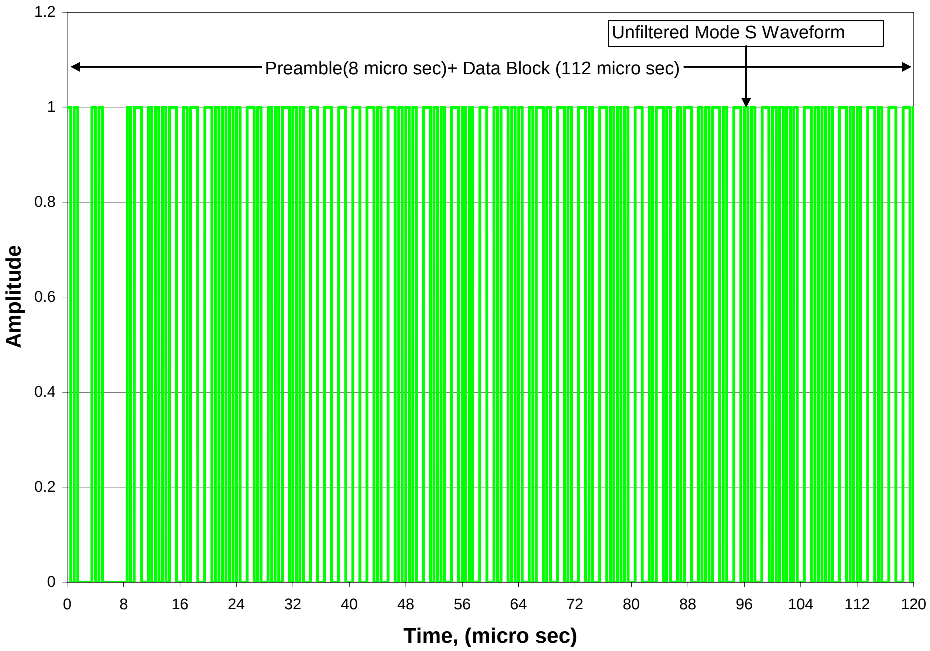
Mode S Transmitter Simulation Model Overview

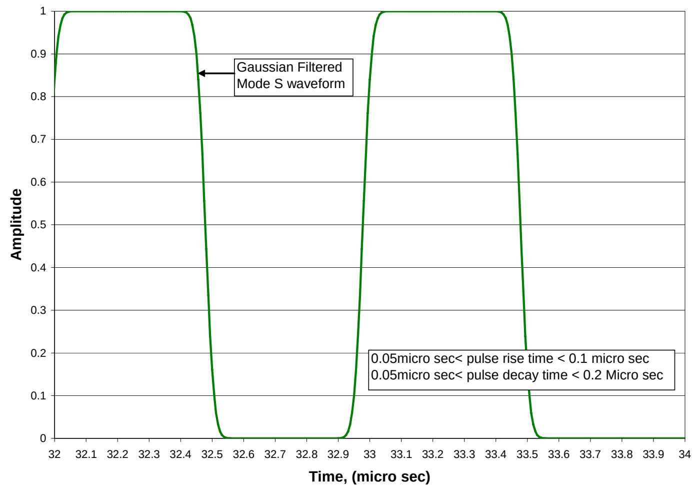
- Mode S transmitter simulation model block diagram overview is as follows:



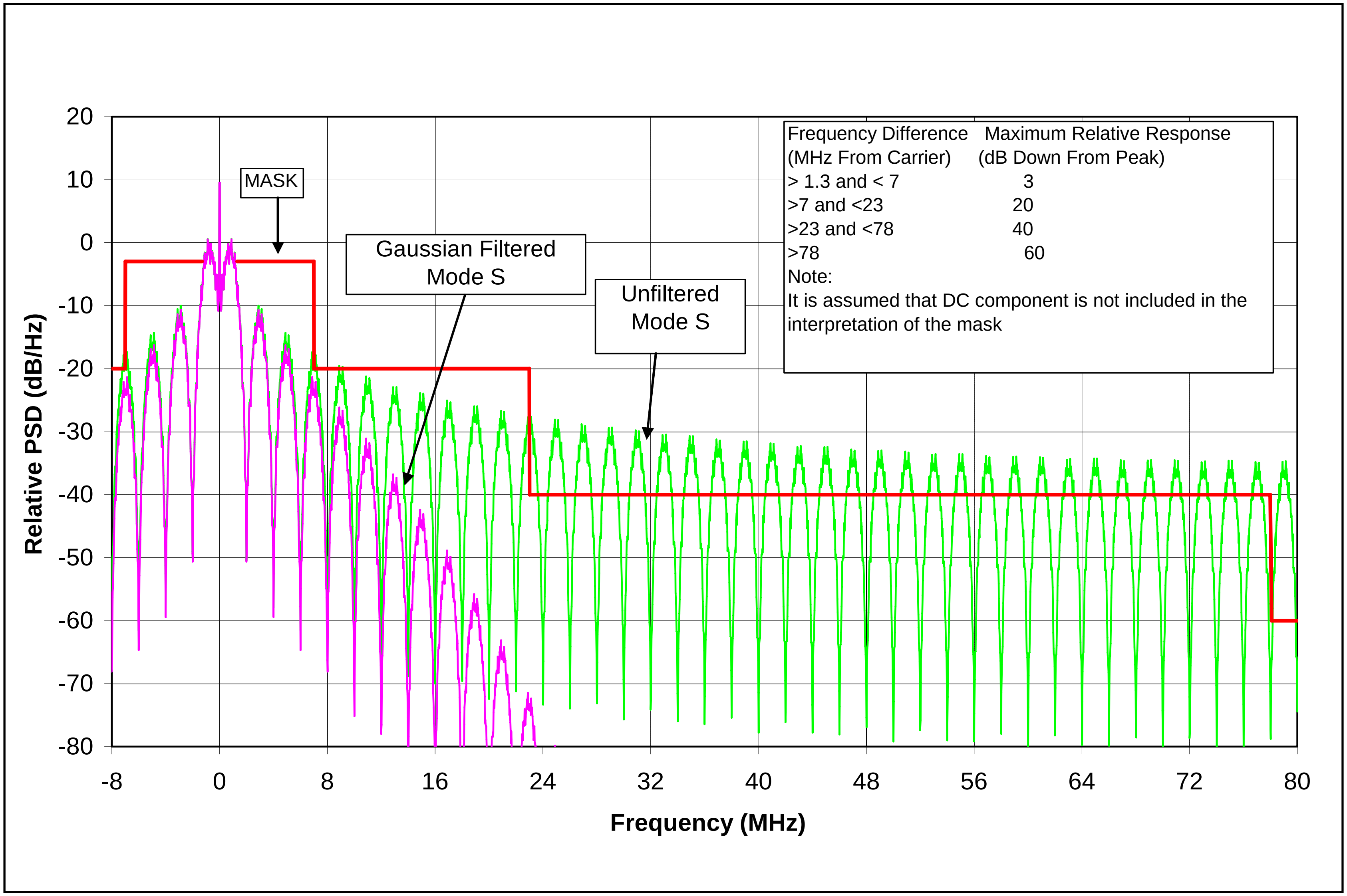
Validating Mode S Model – Generated Waveforms





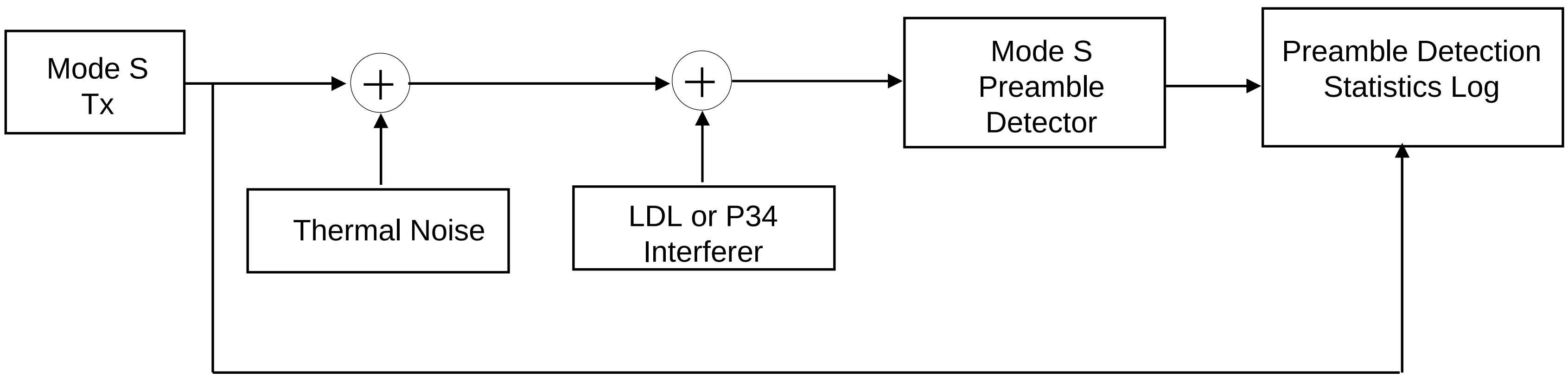


Validating Mode S Model –Comparison of Predicted Emissions to Mask



Mode S End-to-End Simulation Model Overview

- Mode S end-to-end simulation model overview is assumed as follows (includes interferer):

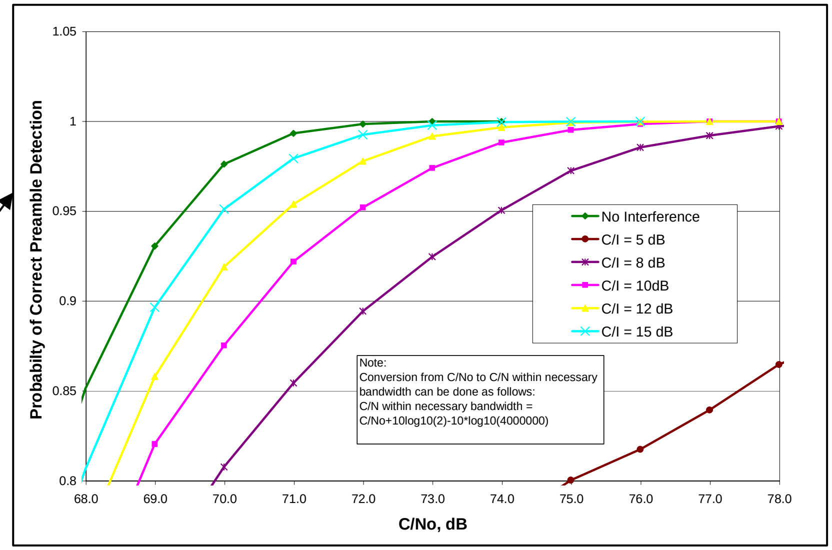


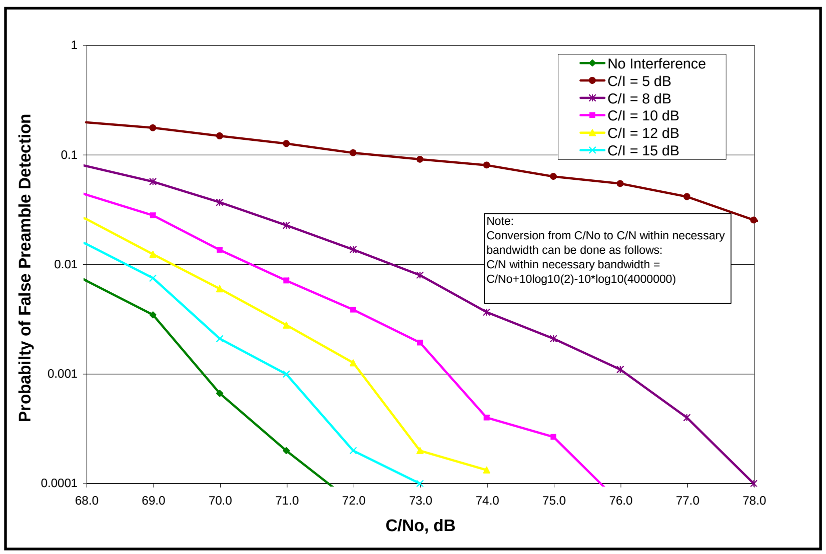
Mode S with LDL Interference at Mode S Center Frequency

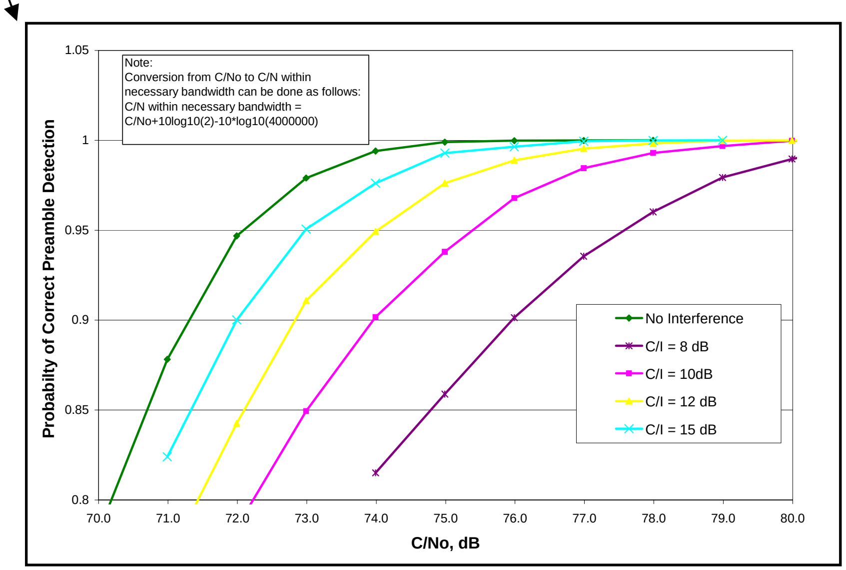
- Probability of correct preamble detection curves
  - Based on an algorithmic assumption to declare preamble detection of

    94% correlation

    100% correlation
- Probability of false preamble detection curves







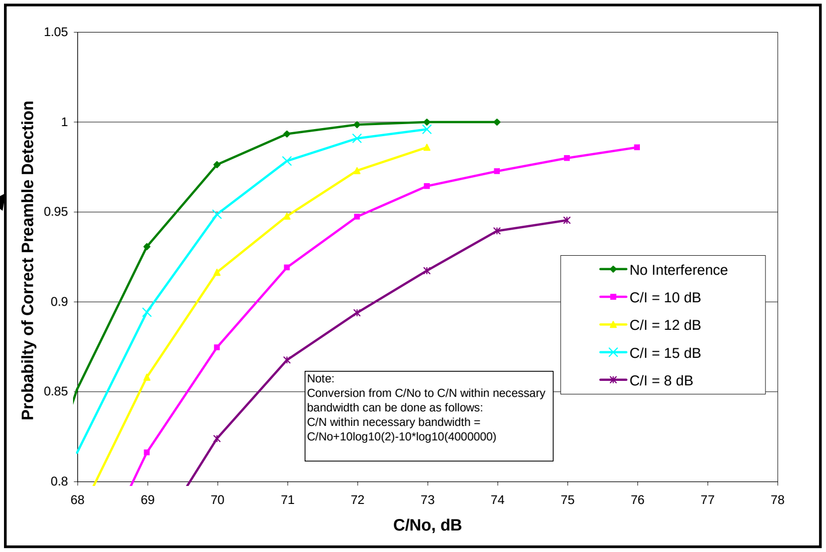
Mode S with P34 Interference at Mode S Center Frequency

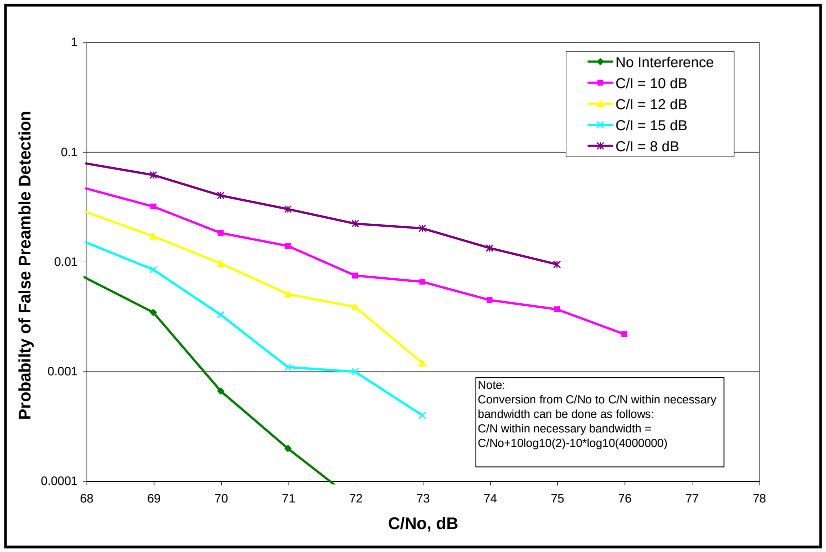
- Probability of correct preamble detection curves
  - Based on an algorithmic assumption to declare preamble detection of

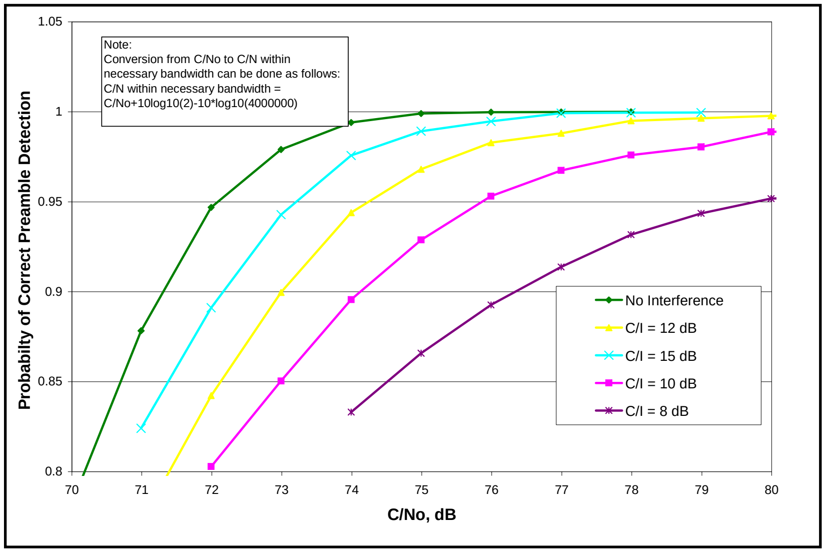
94% correlation

100% correlation

- Probability of false preamble detection curves





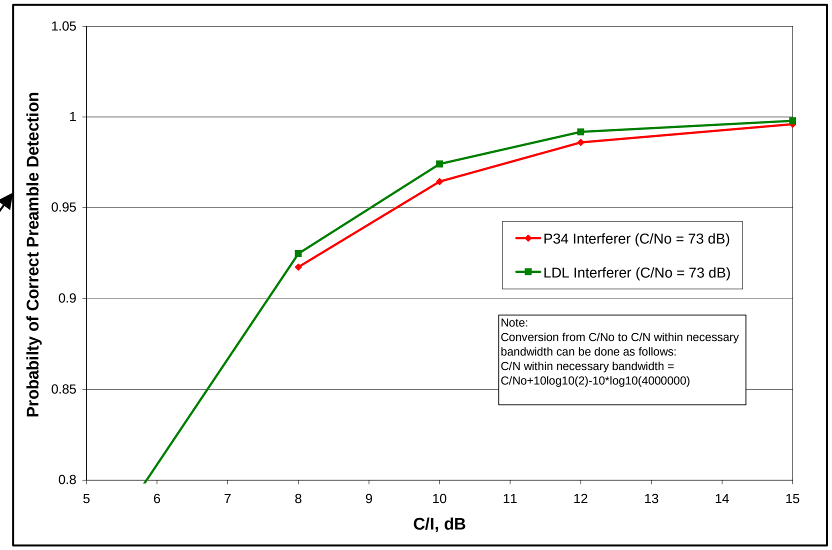


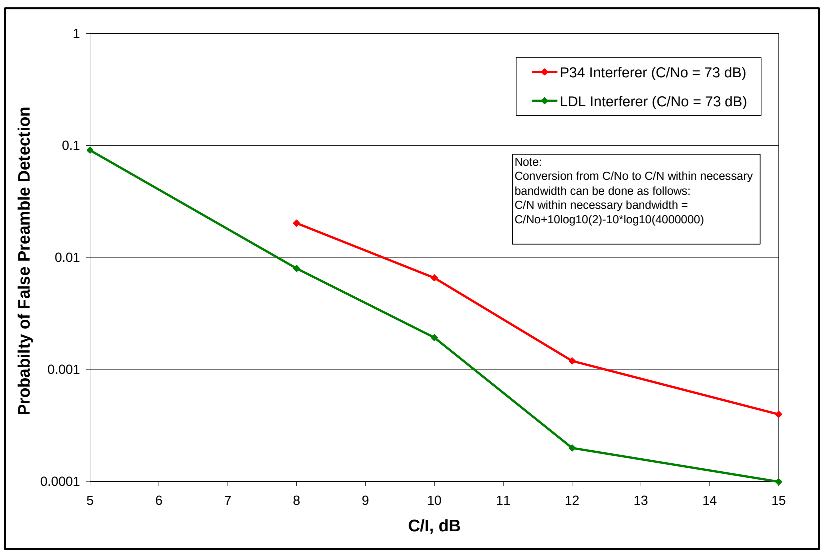
Comparison of P34 and LDL Effects

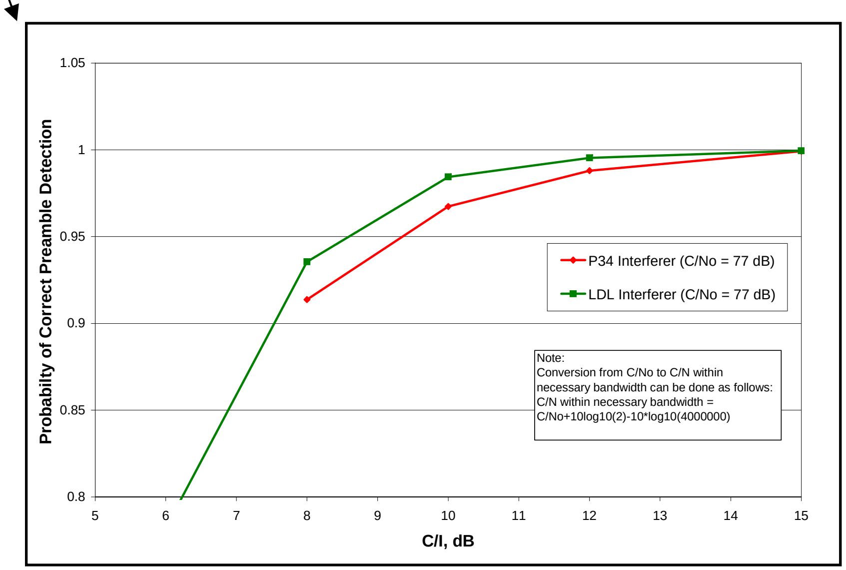
- Probability of correct preamble detection curves
  - Based on an algorithmic assumption to declare preamble detection of

    94% correlation

    100% correlation
- Probability of false preamble detection curves







Conclusions

- The modeling results would seem to indicate that a C/I ratio of 15 dB or better is required to not substantially degrade the Mode-S preamble detection performance
  - The behavior of “false preamble detection” would appear to be somewhat worse than the behavior of “missed preamble detection”
- As in the UAT case, the performance of LDL is better than that of P34 – that is to say, P34 acts as more of an interference source than LDL to both Mode S and UAT receivers
- All simulations were made “on-tune”
  - Actual deployment scenarios should be far off-tune, especially for the Mode S case (proposed band for the FRS is 960-1024 MHz, and the Mode S Extended Squitter equipment is at 1090 MHz)
- Measurements should be made that further characterize Mode S behavior – there are other metrics to investigate besides preamble detection
  - Preamble detection modeled here is hardly sophisticated – better performance from actual equipment is predicted